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Final Report on The Effect of PWHT on HAZ Hardness in A516 Steel

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ABSTRACT

A study was conducted, for the Committee on Thermal and Mechanical Effects of the Pressure Vessel Research Council, to determine the effect of low temperature post weld heat treatments (PWHTs) on the serviceability of the resulting weldment.

Bead-on-plate weldments were placed on A516 plates having two different carbon equivalents, Grade 60 and Grade 70. (The plates were supplied by Lukens Steel.) Two welding heat inputs, 35 kj/in. And 125 kj/in., were used. The weldments were then subjected to a series of PWHTs, and HAZ hardness was monitored as a function of time and temperature. The time and temperature HAZ hardness data were analyzed to determine the Larson-Miller constant, the parameter usually suggested as most reflective of the metallurgical processes occurring during PWHT.

It was found that judgment is needed in the application of the Larson-Miller parameter for analyzing PWHT HAZ softening. The best value for the constant C in the parameter occurs as PWHT approaches completion. It also is strongly dependent on weld heat input. Possibly, the overall effectiveness of a weldment's PWHT cannot be predicted simply by a single parameter.

INTRODUCTION

A recent report by Spaeder and Doty [1] has pointed out some anomalies and inconsistencies in the ASME requirements for post weld heat treatment (PWHT). Spaeder and Doty indicated a compelling need for a comprehensive study to determine the effect of the minimum (time and temperature) PWHT requirements on the notch toughness, hardness, and residual stresses of steels representative of each P number and grade. They suggest that this study could also be the basis for a clear explanation of the intent of the code in imposing PWHT requirements.

The Committee on Thermal and Mechanical Effects of the Pressure Vessel Research Council suggested that the first concern to be addressed be that of the use of low temperature PWHT's and the time-temperature relationships implied by the Code Table UCS-56.1. The Committee acknowledged the necessity for the allowance of lower temperature post weld heat treatments in special cases. For example, when normal PWHT would expose an austenitic stainless steel to sensitizing temperatures, engineering considerations force lower PWHT temperatures. Recognizing that some low temperature post weld heat treatments are a practical necessity, the Committee directed that a review and study be accomplished to provide an understanding of the effect of these type PWHT's on the overall serviceability of the resulting post weld heat treated weldment.

The results reported here are part of a larger general program currently ongoing. The broad goal of the general program is to establish the overall effect of the present PWHT Code requirements on the level of residual stress, strength, hardness and toughness for representative groups of steels. To provide a basis for maintaining or changing the current PWHT requirements, it is desirable to quantify the effect of the present rules on the amount of stress relaxation as well as other metallurgical changes that are induced under the present rules. The effect of the present PWHT practices on the properties (hardness, strength, toughness, etc.) will be evaluated and examined by way of a fitness for purpose concept. The analysis of the data will focus on the improvement or degradation of the tolerance of the welded component or structure to discontinuities as a result to the combined effects of a reduction in residual stresses and changes in toughness and strength.

BACKGROUND

The physical, mechanical and metallurgical changes that occur in a weldment during PWHT are extremely complex. The ASME Code has established PWHT time and temperature requirements as well as possible PWHT exemptions for different groupings of steels. These PWHT parameters are largely based on engineering judgement and experience. Although the present rules have served industry well, advances in the steel making and welding fabrication technology may make it desirable to modify or eliminate some of the PWHT practices.

As suggested by Spaeder and Doty [1], one area of the Code that merits additional examination is the allowance in Table UCS-56.1 to drop the minimum PWHT temperature with some materials by as much as 200°F provided the hold time is increased up to 20 hours/inch. See Table UCS-56.1 from the ASME Code, which follows.

TABLE UCS-56.1
ALTERNATIVE POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS
Applicable Only When Permitted in Table UCS-56

Decrease in Temperature Below Normal Holding Temperature,°F	Minimum Holding Time at Decreased Temperature hr/in, of Thickness,	Notes
50	2	oooo
100	4	oooo
150	10	(1)
200	20	(1)

NOTE:
(1) These lower postweld heat treatment temperatures permitted only for P-No, 1 Gr. Nos. 1 and 2 materials.

Both Gulvin[2] and Stout[3,4] have suggested the metallurgical processes that occur during PWHT can be characterized by the Larson-Miller parameter, LMP = Temp[C + log(time)] x 10^{-3} ,and the equivalent Hollomon-Jaffe parameter. The value of the constant C in these parameters is derived from stress rupture data and for steels is typically taken as 20. An absolute temperature scale is used, either Rankine or Kelvin, and units of time are usually hours. As pointed out by Spaeder and Doty, the work of Gulvin[2] suggests PWHT residual stress reduction can be characterized by the above parameters. For example, to be equivalent to three hours at 1100°F, the hold time at 900°F would be over 3,000 hours. This hold time should be compared with the Table UCS-56.1 values which suggest a 60 hour 900°F PWHT is equivalent to a three-hour 1100°F PWHT. It has been suggested that the short hold times of Table UCS-56.1 were perhaps substantiated by using a different constant, C, in the Larson-Miller relation[5]. Figure 1 shows that a C of 8.8 is required to give a Larson-Miller equivalence for 1 hour at 1100°F as suggested by Table USC-56.1. These hold times as well as similar time-temperature trade-offs contained in other codes are consistent with a Larson-Miller constant, C, between 7 and 9.

Clearly the Larson-Miller parameter is useful, however care needs to be exercised in application, especially when making comparisons of PWHT schedules. As shown later, literature data suggests as PWHT stress relaxation, HAZ hardness softening and yield strength reduction approach completion, the best-fit value for the Larson-Miller constant C becomes smaller. There are however some exceptions to this trend. Thus, while there may be some basis, other than engineering necessity and practicality, for the time-temperature trade-offs currently allowed in ASME codes, the overall effectiveness of a weldment's PWHT cannot be simply predicted by a single parameter.

A recent IIW document [6] contains the recommendation that PWHT temperatures below 600°C (1112°F) may be acceptable if demonstrated to be satisfactory using fracture mechanics analysis. The IIW paper recommends a Larson-Miller parameter of 20 for full stress relief. As discussed below the Europeans tend to work in units of degrees kelvin and hours; thus a parameter of 20 is equivalent to one hour at 1340°F (727°C), (using C = 20) or to a 157 hour PWHT at 1000°F. The European community makes use of the Larson-Miller parameter in PWHT in two ways. They suggest a minimum parameter to achieve sufficient stress relief, as noted above, and a maximum parameter to insure PWHT does not reduce yield strength. In both cases the parameter calculation uses the constant C = 20. Another precaution needs to be noted here is the fact that different authors use different units, principally different temperature scales, when calculating Larson-Miller parameters. Generally work in the USA on creep and stress rupture is reported in a Larson-Miller format using degrees Rankine and time in hours. Tempering studies and most Europeans use temperature in degrees Kelvin and time in hours.

It is sometimes suggested [7] that the ability of the Larson-Miller parameter, and the equivalent Hollomon-Jaffe parameter, to calculate time-temperature equivalencies stems from the assumption that the rate controlling mechanism may be described by an Arrhenius-type rate equation. Many metallurgical processes may be described by an Arrhenius rate equation with the form: Rate = $Ae^{-Q/RT}$. If one assumes the rate remains relatively constant at a constant temperature over time, then the time to reach some arbitrary intermediate state will depend on this rate.

That is, $state_i = t_i \times Rate_i = t \times Ae^{-Q/RT}$, let the state of interest be represented by K, a constant.

$K = t \times Ae^{-Q/RT}$,	dividing by $Ae^{-Q/RT}$ and rearranging
$t = (K/A)\, e^{Q/RT}$,	taking the log to the base 10 of both sides
$\log t = \log(K/A) + (Q/RT)\log e$,	multiplying both sides by T
$T \log t = T \log(K/A) + 0.43Q/R$,	rearranging
$T \log t - T \log(K/A) = 0.43Q/R$,	simplifying
$T(\log(A/K) + \log t) = 0.43Q/R$,	recognizing A/K and Q/R are constant
$T(C + \log t) = P$,	where for a constant state of interest C and P are also constant.

It is interesting to note this derivation of the Larson-Miller Parameter based on an Arrhenius rate controlled process predicts the Larson-Miller parameter is directly proportional to the activation energy of the controlling process and the C constant is function of the state of interest. This suggests that the value of C will depend on the post-weld-heat-treated condition. This also suggests the Larson-Miller parameter will remain constant for all states governed by the same rate controlling metallurgical mechanism. Thus, although the form of the Larson-Miller parameter is predicted by the Arrhenius rate equation, the functional relationship among the various terms of the Larson-Miller parameter are not indicated by this analysis. Nevertheless, significant experimental data analyzed using the Larson-Miller parameter has illustrated the utility of this parameter for time-temperature equivalence. The value of the constant C is generally determined empirically from stress rupture and creep experiments. Typically for steels this constant is in the range of 18 to 20.

Thus, the above derivation suggests the Larson-Miller constant C is related to the state of interest and may in fact vary if the state of interest changes. For example, consider the data of Goodwin and Nanstad [8]. They conducted stress relaxation test on simulated HAZ specimens over a range of times and temperatures. Table II shows the results of these experiments. These data are useful in that they are one of few that allow comparison of known constant states, that is levels of constant stress reduction, as a function of time and temperature. Larson-Miller parameters (LMP) can be calculated for each result within the columns of constant percent of stress relief. The results within that column were compared in order to determine the best Larson-Miller constant, C, by least-squares fit of the data as described later in this report. The result of this analysis is shown in Figure 2. For this data the value of C ranges from 25 to 10, with the lower values associated this higher percent stress reduction.

TABLE II
Stress Relaxation in ASME SA-533 Grade B Steel[a](from ref.[8])

Temp	Stress (ksi)		σ_{20}/σ_0	Time (sec.) to various fractions of σ_0								
(°F)	σ_0	σ_{20}	(%)	0.9	0.85	0.8	0.75	0.7	0.6	0.5	0.4	0.3
900	63.9	50.0	78	26	161	661	>1200	>1200	>1200	>1200	>1200	>1200
950	65.1	50.4	78	15	85	451	>1200	>1200	>1200	>1200	>1200	>1200
1000	63.0	46.5	74	14	70	253	808	>1200	>1200	>1200	>1200	>1200
1050	63.6	46.5	73	12	42	132	468	>1200	>1200	>1200	>1200	>1200
1100	67.7	43.6	64	6	16	54	111	>1200	>1200	>1200	>1200	>1200
1150	60.4	33.9	56	8	22	42	71	131	615	>1200	>1200	>1200
1200	63.0	26.8	43	2	4	6	12	23	89	380	>1200	>1200
1250	63.5	16.0	25	0.5	1	2	4	8	22	72	192	549

Early work by Rominsky and Taylor[9] suggest for 100% stress relief of steel castings the appropriate C value is 10. Figures 3 and 4 show the effect of time and temperature on stress relaxation in carbon steel. [10, 11] Calculation of a Larson-Miller parameter from these plots suggests a constant of 15 to 16 from Figure 3 and 20 to 21 from Figure 4. Figure 4 originated in a 1946 publication of Jelm and Herres [12]. It is believed that Figure 3 originated from the work of McDowell and Cunnick published in the Welding Journal October 1944 [13].

The relaxation of stresses during PWHT is not the only process that must be considered. Equally important are the changes in mechanical properties that can occur. It is well known that changes in yield strength, hardness and toughness occur during PWHT. The metallurgical processes that control these changes do not necessarily lend themselves to simple parametric quantification by relationships like the Larson-Miller parameter. Consider, for example, a HAZ in a microalloyed steel which undergoes a precipitation hardening reaction during PWHT with eventual overaging and softening on continued PWHT. Clearly the PWHT time-temperature hardness equivalence in this case will not be predicted by a simple empirical relation.

Other complicating factors must be addressed in order for a complete understanding of the effect of PWHT. The heterogeneity of the weld zone is perhaps the most difficult aspect of this problem. As one traverses from weld metal across the HAZ into the base metal, one encounters changes in composition, changes in grain shape and size, changes in precipitation size and morphology, variation in residual stress, and changes in phase mixtures. Each of these heterogeneities can have a significant effect on the PWHT response. For example, consider the effect of grain size on creep rate. Ashby [14] has shown that at some stress-temperature environments one can observe significant differences in creep rate due to grain size differences. Lundin [15] has reported up to three orders of magnitude increase in creep rate in simulated fine grain HAZs as compared to coarse grained regions. Variations in constituent phases also have the potential for introducing significant variation in the PWHT response of a weldment. The intrinsic metallurgical differences between austenite and ferrite yield large differences in diffusivity and creep rates.

Other analyses[16] of literature data (stress relaxation, PWHT hardness, PWHT yield strength and Charpy V-notch toughness) generally showed the best value for the Larson-Miller constant C varied somewhat but generally was found to be near 20. However some data was best fit with a C constant as low as 5 and other data with a C constant as high as 45.

EXPERIMENTAL PROGRAM

These studies used A516 plates of two different carbon equivalents utilizing two welding heat inputs. Bead-on-plate weldments were subjected to a series of PWHT's and the HAZ hardness was monitored as a function of time and temperature. The hardness measurements were taken to monitor the progression of the softening of the maximum hardness in the HAZ by a method suggested by B. Graville[17]. Five measurements are taken on each of five sections and an average of the maximum hardness noted in each section is calculated. The measurements are all taken in the HAZ within 0.4mm of the fusion line. See Figure 5. The weld parameters for the 35 kJ/in and 135kJ/in FCAW bead-on-plate welds are shown in Table III. The matrix of PWHT times and temperatures are shown in Table IV. The bead-on-plate welds were to be made in 30 inch lengths and cut into six five inch long samples and given PWHT's as indicated in Table IV. Following PWHT each sample was to be sectioned at five locations and each section metallographically prepared and the maximum hardness in the HAZ determined. The procedures used to fit the measured hardness data to a Larson-Miller type model is described below.

Table III
Weld Parameters

Weld Parameters - Low Heat Input	
Process	Flux Cored Arc Weld
Wire	0.045" dia. E71T
Current	175 amps
Voltage	30 volts
Travel Speed	9 in/min
Heat Input	35 kJ/in
Weld Parameters - High Heat Input	
Process	Flux Cored Arc Weld
Wire	0.062" dia. E71T
Current	350 amps
Voltage	30 volts
Travel Speed	5 in/min
Heat Input	125 kJ/in

Table IV
PWHT Time-Temperature Matrix

PWHT TEMP. (Deg.F)		TIME AT TEMPERATURE, Hours					
		0.5	1	2	5	10	20
	1200	X	X	X			
	1150	X	X	X			
	1100	X	X	X	X		
	1050		X	X	X	X	
	1000		X	X	X	X	X
	950			X	X	X	X
	900			X	X	X	X

In addition to the time-temperature schedules indicated by the matrix in Table IV samples at 1000°F, 1100°F and 1200°F were heated to temperature and immediately cooled. This was done to examine the amount of softening that occurs on heat up. All samples but one were heated up at the rate of 78 °F/hr. An additional Grade 60 low heat input sample at 1000°F was heated at a rate of 156°F/hr. In all cases the samples were cooled in air after the PWHT. The cooling rate was nominally 600°F/hr.

Two grades of ASTM A516 were supplied by Lukens Steel for this project. The composition and mechanical properties of the Grade 60 and Grade 70 A516 plates are given in Table V.

Analytical Procedure The following procedure was used to determine the Larson-Miller constant C in the relation, (LMP)=Temp[C+log(time)] x 10^{-3}, which best fit the experimental data. The assumption is made that PWHt's which produce similar HAZ softening will have similar Larson-Miller parameters. This procedure uses the measured maximum hardness in the HAZ as a function of PWHT time and temperature to determine the time-temperature relation for PWHT's which yields equivalent HAZ hardness. Similar procedures can used for PWHT equivalency as indicated by measurements of stress relaxation, strength, toughness, or any other property that is effected by PWHT.

First the measured HAZ hardness data (or other data of interest) is plotted with hardness on the ordinate (vertical) scale and PWHT temperature on the abscissa (horizontal) scale. The data was then examined to select time and temperature combinations that resulted in equivalent hardness in the HAZ. Thus on the plot of hardness vs. PWHT temperature, a horizontal line (constant hardness) intersects several iso-time hardness data sets, giving time-temperature PWHT combinations which yield identical HAZ hardness, see Figure 6. Thus, for a single hardness one might have three to five time-temperature (t,T) combinations, depending on the amount of overlap in the original data set. For the maximum HAZ data sets time-temperature equivalencies were determined at increments of 5 DPH.

For these equivalent (t,T) points, calculate a LMP using a first trial LMP C. The number 20 is probably a good first trial C value. For the set of equivalent (t,T) points, calculate the average LMP, LMP_{ave}. Using this LMP_{ave} value calculate for each (t,T) point in this equivalency set the predicted temperature T_p as follows:

$$T_p = (LMP_{ave})/(C+\log(t)) \ .$$

Table V
Steel Plate Composition and Properties

A516 Grade 60 - 1.25 inch plate
COMPOSITION

C	Mn	P	S	Cu	Ni	Cr	Mo	Si	V	Al	C.E.*
0.16	0.92	0.015	0.011	0.22	0.13	0.21	0.03	0.19	0.004	0.02	0.385

MECHANICAL PROPERTIES

	Yield	Tensile	E in 2"	CVN (ft-lb) - traverse	
Location	(ksi)	(ksi)	(%)	-50°F	0°F
TX	48.0	72.8	29	26, 29, 30	33, 41, 42
BX	43.8	69.5	30	22, 22, 22	37, 38, 41

A516 Grade 70 - 1.25 inch plate
COMPOSITION

C	Mn	P	S	Cu	Ni	Cr	Mo	Si	V	Al	C.E.*
0.26	0.96	0.007	0.002	0.15	0.13	0.10	0.02	0.24	0.002	0.01	0.463

MECHANICAL PROPERTIES

	Yield	Tensile	E in 2"	CVN (ft-lb) - traverse	
Location	(ksi)	(ksi)	(%)	-50°F	0°F
TX	54.8	81.4	31	24, 31, 46	56, 72, 75
BX	53.3	82.0	29	26, 34, 40	48, 58, 64

[8]C.E. = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15

Minimize the square of the difference between the predicted and actual temperatures,

$$(T_p - T_{act})^2 ,$$

by an iterative technique by varying the LMP constant C using a step size for C of 0.1. The C value which minimizes the square of the differences is taken as the best C for this data.

Contribution to PWHT by the Heat-Up Portion of the Thermal Cycle One should recognize that the Larson-Miller Parameter (LMP) is not additive. For example, if it is assumed the heat-up portion is relatively short, it can reasonably be expected that two consecutive 10 hour PWHT's at 1000°F will have the same result as one 20 hour PWHT at 1000°F. Thus, if one accepts the premise that equivalent PWHT's have the same LMP, the LMP for the 20 hour 100°F PWHT should be the same as the LMP for the two combined 10 hour 1000°F PWHT's. The LMP for each 10 hour 1000°F PWHT separately is, LMP_{10}= (1000+460)(C + log(10)). If the Larson-Miller is taken as 20 then, LMP_{10}= 30,660. If the LMP for each of the 10 hour 1000°F PWHT's are added the result is 61,320. However the LMP for the 20 hour 1000°F PWHT is, LMP_{20}= (1000+460)(20 + log(20)) = 31,000. Clearly, for this equivalence only the times can be added.

One should also recognize that only time or equivalent time at identical temperatures can be added to obtain the LMP. For example, if one wants to determine what 1100°F PWHT is equivalent to a 20 hour PWHT at 1000°F followed by a 10 hour PWHT at 1200°F, one can first calculate the total LMP for the combined PWHT and then calculate an equivalent time at 1100°F which gives the same LMP. To calculate the combined PWHT LMP the time at either temperature must be converted to an equivalent time at the other temperature.

$$LMP_{20@1000} = (1000+460)(20+\log(20)) = 31{,}100$$
$$LMP_{10@1200} = (1200+460)(20+\log(10)) = 34{,}860$$

To convert time at 1000°F to equivalent time ($t_{eq\text{-}1200}$) at 1200°F:

$$LMP_{20@1000} = 31{,}100 = (1200+460)(20+\log(t_{eq\text{-}1200}))$$
$$\log(t_{eq\text{-}1200}) = (31{,}100/1660) - 20$$
$$t_{eq\text{-}1200} = 10\ \exp[(31{,}100/1660) - 20] = 10^{-1.265} = 0.0543\ \text{hour}$$

Now one can sum the time at 1200°F to get the total LMP.

$$LMP_{tot} = (1200+460)(20+\log(10+0.0543) = 34{,}869$$

To calculate an equivalent PWHT at 1100°F:

$$LMP_{?@1100} = 34{,}864 = (1100+460)(20+\log(t_{eq\text{-}1100}))$$
$$t_{eq\text{-}1100} = 10\ \exp[(34{,}864/1560)-20] = 223\ \text{hours}$$

Alternatively, one can calculate the equivalent time at 1100°F for each of the two original PWHT's and then add the results:

$$LMP_{20@1000} = 31{,}100 = (1100+460)(20+\log(t_{eq\text{-}1100}))$$
$$t_{a\text{-}eq\text{-}1100} = 10\ \exp[(31{,}100/1560)-20] = 0.86\ \text{hour}$$

$$LMP_{10@1200} = 34{,}860 = (1100+460)(20+\log(t_{eq\text{-}1100}))$$
$$t_{b\text{-}eq\text{-}1100} = 10\ \exp[(34{,}860/1560)-20] = 221.9\ \text{hour}$$
$$t_{eq\text{-}1100} = t_{a\text{-}eq\text{-}1100} + t_{b\text{-}eq\text{-}1100} = 223\ \text{hours}$$

To determine the time equivalent for the heat-up portion of a PWHT, one can divide the time-temperature trace into small time increments, Δt, and calculate the time, Δt_{eq}, at the PWHT hold temperature, T_{hold}, that is equivalent to the time and temperature of this small increment. Summing all these time increments from the initial temperature, T_o, to the beginning of the steady state hold temperature, T_{hold}, will give the time equivalent for the heat-up portion of the PWHT.

At any increment of time, Δt_i, between T_o and T_{hold}:

$$T_i(C+\log(\Delta t_i)) = T_{hold}(C+\log(\Delta t_{eq})$$
$$C+\log(\Delta t_{eq}) = (T_i/T_{hold})(C+\log(\Delta t_i))$$
$$\Delta t_{eq} = 10\ \exp[(T_i/T_{hold})(C+\log(\Delta t_i)) - C]$$

Assuming the heat-up portion of the PWHT is linear with a heat rate of K (deg.F/hour)

$$T_i = T_o + Kt_i$$

Thus,

$$\Delta t_{eq} = 10 \exp[((T_o + Kt_i)/T_{hold})(C+\log(\Delta t_i)) - C]$$
$$t_{eq} = \sum \Delta t_{eq} = \sum 10 \exp[((T_o + Kt_i)/T_{hold})(C+\log(\Delta t_i)) - C]$$

The question of heating and cooling effects during PWHT has been treated mathematically by Eriksson [18]. He has shown the above expression can be represented as:

$$t_{eq} = T_i/(2.3K(C-\log(K)), \text{ where K is the heating rate,}$$

Notice the initial temperature has negligible effect and does not appear in this expression. This expression is used successfully by numerous researchers. [2, 19]

When there is a significant contribution to the PWHT during heating up, some allowance needs to be made in the above determination of the LMP constant C. This is handled as follows: For each time-temperature set in an equivalency group, calculate a time equivalency (t_{eq}) for the heat-up portion. This t_{eq} is the equivalent time at the hold temperature which gives the same effect as the heat-up portion of the PWHT. Eriksson[4] has suggested t_{eq} can be expressed as

$$t_{eq} = T_i/(2.3K(C-\log(K)), \text{ where K is the heating rate,}$$

Calculate a LMP for each time-temperature set:

$$LMP_i = T_i(C+\log(t_{eq}+ t_i)$$

For each equivalency group calculate an average LMP (LMP_{ave}). Using this LMP_{ave} value calculate for each (t,T) point in this equivalency set the predicted temperature T_p as follows:

$$T_p = (LMP_{ave})/(C+\log(t_{eq} + t))$$

Minimize the square of the difference between the predicted and actual temperatures,

$$(T_p - T_{act})^2$$

by an iterative technique by varying the LMP constant C using a step size for C of 0.1.

When this iterative technique is used individually in each hardness equivalency set it is found that the best fit LMP constant C varies somewhat with the hardness. This leads to an apparent difficulty in this analysis. The calculated time equivalence on heating to a specific temperature is found to vary depending on how long the piece is subsequently held at that temperature. That is, although the heat-up portion (time-temperature trace) of the PWHT is identical, the calculated effective time is different depending on the subsequent hold time. Clearly, this is not reasonable. In these cases the heat time equivalence should be the same irrespective of the subsequent hold time. This apparent difficulty can be avoided if a single LMP constant C is assumed for the all equivalency data sets for one material and heat input. This best single C can be determined by using the same C through all equivalency sets and minimizing the square of the differences between all predicted and actual temperatures for all equivalency sets simultaneously. When the best single C is used the hardness vs. LMP plot results in a nearly linear relationship with a fairly tight grouping of the data. Using the maximum HAZ hardness gives a slightly tighter grouping than the average HAZ hardness.

Using the above procedure it is likely best to use the raw data rather than a curve smoothing or fitting operation. This avoids any bias that the fitting of the original data might introduce. Analysis of the raw data appears give a result similar the analysis of the linear fit data. The best fit single C value derived from the raw maximum HAZ data is only one or two units different than the best fit single C value from the linear fit max. HAZ data. Both these analyses took into account the heat-up effect.

RESULTS

The PWHT HAZ hardness measurements are summarized in Table VI and Figures 7 through 9. These data were collected by selecting the maximum of the five fusion-line HAZ hardness readings taken on each metallographic section. As there were five sections made of each PWHT specimen, each datum entry in Table VI represents and average of five maximum readings from five metallographic sections. Figures 10 through 12 summarize the microstructures observed in the as-welded and post-weld-heat-treated A516 Grade 60 - low heat input samples. The micrographs are taken from the fusion-line area, showing a typical micro-hardness indentation.

Table VI
HAZ Hardness as a Function of PWHT

Time (HRS)	TEMP (DEG F) 1200	1150	1100	1050	1000	950	900
	Low heat Input			A516 Gr.60		as-welded HAZ, 387DPH	
0.5	224.0	245.0	254.0				
1	218.3	237.0	251.2	267.3	273.3		
2	213.8	232.7	255.0	264.0	273.6	279.0	298.5
5			237.0	260.0	273.4	277.8	294.3
10				251.0	269.7	275.0	288.7
20					259.6	274.0	280.5
	Low heat Input			A516 Gr.70		as-welded HAZ, 453DPH	
0.5	237.7	261.0	273.3				
1	228.0	251.7	267.0	285.7	291.7		
2	222.3	245.0	265.0	280.3	286.7	297.0	315.3
5			251.7	271.3	283.7	291.7	306.3
10				267.3	284.0	288.7	302.7
20					272.7	284.3	300.3
	High heat Input			A516 Gr.60		as-welded HAZ, 308DPH	
0.5	219.3	230.7	234.0				
1	218.7	228.0	234.0	236.3	239.0		
2	215.3	228.3	233.3	235.0	238.0	247.7	261.0
5			230.0	237.3	238.0	245.3	259.7
10				234.7	236.7	244.0	256.3
20					236.7	242.3	255.7

The results of the analysis of the best Larson-Miller C constant outlined above are summarized in Table VII. The C constant analysis was conducted on the A516 Grade 60 - low heat input data using both the average of maximums and the overall average of all HAZ hardness readings. As illustrated in Figure 13, the average of maximum HAZ hardness runs parallel to the overall average. Typically the overall average data is 8 to 10 DPH lower. Using the single LMP C method, the analyses of both the maximum and overall average gave essentially identical C values - 24.5 for the maximum set and 24.25 for the overall average set. Using the maximum HAZ hardness gives a slightly tighter grouping than the average HAZ hardness.

Figure 14 shows the twenty-seven data entries from Table VI Grade 60 - low heat input results plotted versus Larson-Miller parameter using the Larson-Miller C constant of 24.5. Figures 15 and 16 show similar plots for the maximum hardness data for the Grade 70 - low heat input and the Grade 60 - high heat input.

Table VII
Larson-Miller C constants

Base Plate and Welding Conditions	Larson-Miller C constant
A516 Grade 60 - low heat input	24.5
A516 Grade 70 - low heat input	19.8
A516 Grade 60 - high heat input	56.3

Results for the samples heated to temperature and immediately cooled are in Table VIII.

Table VIII
Heat-Up Sample Results

Maximum Temp. (°F)	Heat Rate (°F/hr.)	Maximum HAZ Hardness (DPH)
Grade 60 - 35 kJ/in		
1200	78	217
1100	78	260
1000	78	286
1000	156	288
Grade 70 - 35 kJ/in		
1200	78	244
1100	78	271
1000	78	288
900	78	326
Grade 60 - 125 kJ/in		
1200	78	221
1100	78	238
1000	78	245
900	78	261

* Effective time = $T_{max}/(2.3(\text{heat rate})(C-\log(\text{heat rate})))$, Larson-Miller constant C from analysis of HAZ hardness data [18]

DISCUSSION

When comparing Figures 7 through 9 it is apparent the higher heat input data is grouped closer together. That is, at the high heat input the hardness equivalency among the short time and long time PHWT's occur at temperatures which are closer together compared to the low heat input data. For example, the temperature span for equivalent hardness at 273 DPH between the 20 hour PWHT and the 1 hour PWHT is approximately 80°F for the A516 Grade 70 low heat input. For the A516 Grade 60 low heat input the temperature span for a 260 DPH hardness equivalency between the 20 hour PWHT and the 1 hour PWHT is approximately 75°F. While for the A516 Grade 60 high heat input the temperature span fora 237 DPH hardness equivalency between the 20 hour PWHT and the 1 hour PWHT is approximately 50°F.

This closer grouping of the hardness data leads to the larger value of the C constant. As seen in Figure 1, the larger the value of the C constant in the Larson-Miller parameter, the flatter the time-temperature equivalence relationship. This tighter grouping of the data for the high heat input should be expected. This is because at this higher heat input the maximum as-welded HAZ hardness is lower than that of the lower heat inputs. Thus there is less softening available for the high heat input HAZ. Therefore, one might expect that as the heat input decreases the best fit C constant for the Larson-Miller parameter will also decrease. The same trend might also be expected as carbon contents are increased.

As mentioned earlier the examination of the heat-up specimens was accomplished to determine the amount of softening that occurs on heat-up. All samples but one were heated up at the rate of 78 °F/hr. An additional Grade 60 - low heat input sample at 1000°F was heated at a rate of 156°F/hr. As seen in Table VIII, although this difference in heating rate had little effect, it is clear that a significant portion of the softening occurs during the heat-up portion of the PWHT cycle. For example, the Grade 70 - low heat input sample which had an as-welded HAZ hardness of 453 DPH was softened to 271 DPH while heated to 1100°F. Subsequent holding at 1100°F for 2 hours reduced the hardness only an additional 6 DPH to 265 DPH.

Good agreement is obtained when one uses the data from Table VI and VII to predict the HAZ softening during the heat-up portion of the PWHT cycle. From a plot of measured hardness versus the Larson-Miller parameter, using the C values from the above analyses, it is possible to predict the HAZ hardness for any time-temperature treatment, see Figure 17. Treatment of varying temperature can be handled using the suggested form of Eriksson [18]. Table IX below shows a comparison of the actual measured max. HAZ hardness and the predicted hardness. As can be seen the agreement is reasonably good.

In a manner similar to the predictions above it is possible to predict the softening that results from any typical PWHT of these two steels. If one selects the PWHT heat-up rate, hold temperature and hold time, then using the Larson-Miller model and the relationships between the Larson-Miller parameter and the PWHT HAZ hardness shown in Figures 14, 15 and 16 along with the Eriksson formulation for effective heat-up time [18], it is possible to follow the progression of softening in the HAZ as the PWHT proceeds. The plots in Figures 18 and 19 illustrate this. In these plots the HAZ softening is shown as a percentage of the difference between the maximum HAZ hardness and the as-received base plate hardness. These plots show the progression of softening in the Grade 70 plate for two of the allowed ASME Table UCS-56.1 PWHT schedules for these P1 materials. Figure 18 shows the softening for A516 Grade 70 - low heat input weldment with a 250 °F/hr heat-up rate and a 1 hour - 1100°F PWHT. Figure 19 illustrates the softening during a 20 hour - 900°F PWHT for the same weldment. These results are also summarized in Table X. As noted above, one interesting characteristic in all these predictions is that a significant portion, approximately 90%, of the HAZ softening during PWHT occurs during the heat-up portion of the PWHT.

Table IX
Heat-Up Specimens - Actual vs. Predicted HAZ Hardness

Maximum Temp. (°F)	Heat Rate (°F/hr.)	Effective Time at Max. Temp. (hours)	Maximum HAZ Hardness (DPH)	
			Actual	Predicted
Grade 60 - 35 kJ/in				
1200	78	0.409	217	233
1100	78	0.384	260	259
1000	78	0.360	286	285
1000	156	0.182	288	289
Grade 70 - 35 kJ/in				
1200	78	0.516	244	248
1100	78	0.485	271	276
1000	78	0.454	288	304
900	78	.0423	326	332
Grade 60 - 125 kJ/in				
1200	78	0.170	221	222
1100	78	0.160	238	234
1000	78	0.150	249	248
900	78	0.139	261	259

* Effective time = $T_{max.}$/(2.3(heat rate)(C-log(heat rate))), Larson-Miller constant C from analysis of HAZ hardness data [18]

The effect of heat-up rate is illustrated in Figure 20. This plot shows the effect of heat rate for a 1 hour @ 1100°F PWHT of an A516 Grade 70 - 35 kJ/in weld. It is noted that above about 50°F/hr heat-up rate the softening result of the PWHT is relatively independent of heat-up rate. However, at heat-up rates slower than approximately 25°F/hr the PWHT softening is strongly dependent on the rate of heating. Similar trends are seen in Figure 21 for the other Table UCS-56.1 PWHT schedules although the break in the curve occurs at slower rates as the PWHT hold temperature is lowered.

The predicted difference in HAZ hardness that results from a 1 hour @ 1100°F versus a 10 hours @ 950°F PWHT is illustrate in Figure 22. For a Grade 70 - low heat input weldment a 25 DPH difference is predicted at a heat-up rate of 100°F/hr. That is, at a heat-up rate of 100°F/hr the 10 hours @ 950°F PWHT is predicted to result in a HAZ that is approximately 3 Rockwell C points harder than the 1 hour @ 1100°F PWHT. However, at slower heat rates the difference can become significant. A similar prediction is shown in Figure 23 for the Grade 60 - high heat input weldment. This plot shows the predicted hardness difference is even smaller.

Table X
Effect of Heat-Up Rate on HAZ Softening - A516 Steel

Hold Temp (°F)	Hold Time (hr.)	Heat-up Rate (°/hr)	Percent Softened	PWHT HAZ Hardness (DPH)	Percent Softened	PWHT HAZ Hardness (DPH)	Percent Softened	PWHT HAZ Hardness (DPH)
			Grade 60 - 35 kJ/in		Grade 70 - 35 kJ/in		Grade 60 - 125 kJ/in	
1100	1.0	250	58	251	82	267	50	232
		100	59	250	82	265	50	232
		25	60	249	85	260	50	231
		10	62	243	87	254	51	231
1050	2.0	250	55	260	78	275	46	237
		100	55	260	78	275	46	237
		25	56	258	80	271	47	236
		10	57	255	82	267	47	236
1000	4.0	250	51	269	74	284	43	242
		100	51	269	74	283	43	242
		25	51	268	75	282	43	242
		10	52	266	76	279	43	242
950	10.0	250	48	277	71	291	40	247
		100	48	277	71	290	40	247
		25	48	276	72	290	40	247
		10	48	275	72	288	40	247
900	20.0	250	44	286	67	300	36	252
		100	44	286	67	299	36	252
		25	44	286	68	299	36	252
		10	44	285	68	298	36	252

CONCLUSIONS

Clearly the Larson-Miller parameter is useful, however care needs to be exercised in application, especially when making comparisons of PWHT schedules. The trend often repeated in the above analyses is that time-temperature equivalence is best predicted with smaller LMP constants as the PWHT process approaches completion. That is, as stress relaxation, hardness and yield strength reduction approach completion, the best value for the Larson-Miller constant C becomes smaller. There are however some notable exceptions to this trend.

It is also clear that the Larson-Miller parametric analysis models the PWHT HAZ softening behavior well. However the C constant in the parameter must be adjusted to give the best fit of the data. From the trends observed in the A516 weldment data this C constant will be close to 20 for low heat input weldments and/or high carbon content. As the heat input increases the C constant is expected to increase. At a heat input of 125 kJ/in the best fit C constant for the Larson-Miller parametric model of the PWHT HAZ softening was 56.3 for the A516 Grade 60 weldment.

In typical PWHT most of the HAZ softening occurs during the heat-up portion of the heat treatment cycle. For A516 plate at heat-up rates greater then approximately 100°F/hr. the HAZ hardness differences due to PWHT time-temperature substitutions allowed by Table UCS 56.1 of the ASME Code are predicted to be less the 3 or 4 R_c for temperature drops of up to 100°F. Thus there may be some basis, other then engineering necessity and practicality, for the time-temperature trade-offs currently allowed in ASME codes. However the overall effectiveness of a weldment's PWHT cannot be simply predicted by a single parameter.

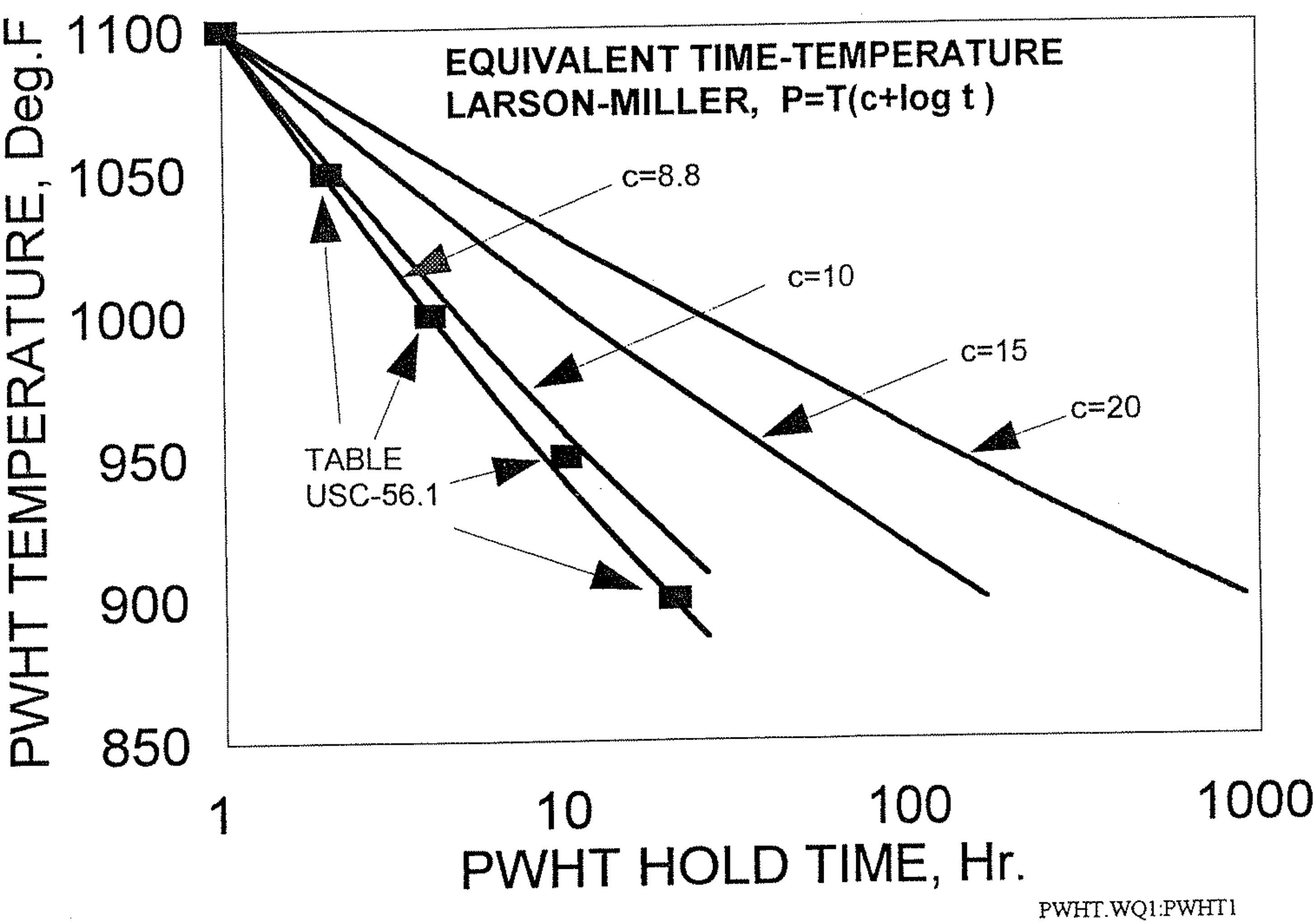


Figure 1: Plot showing the time-temperature equivalency predicted by various Larson-Miller C constants. Comparison is made with ASME Table UCS 56.1 allowances for a one hour - 1100°F post weld heat treatment.

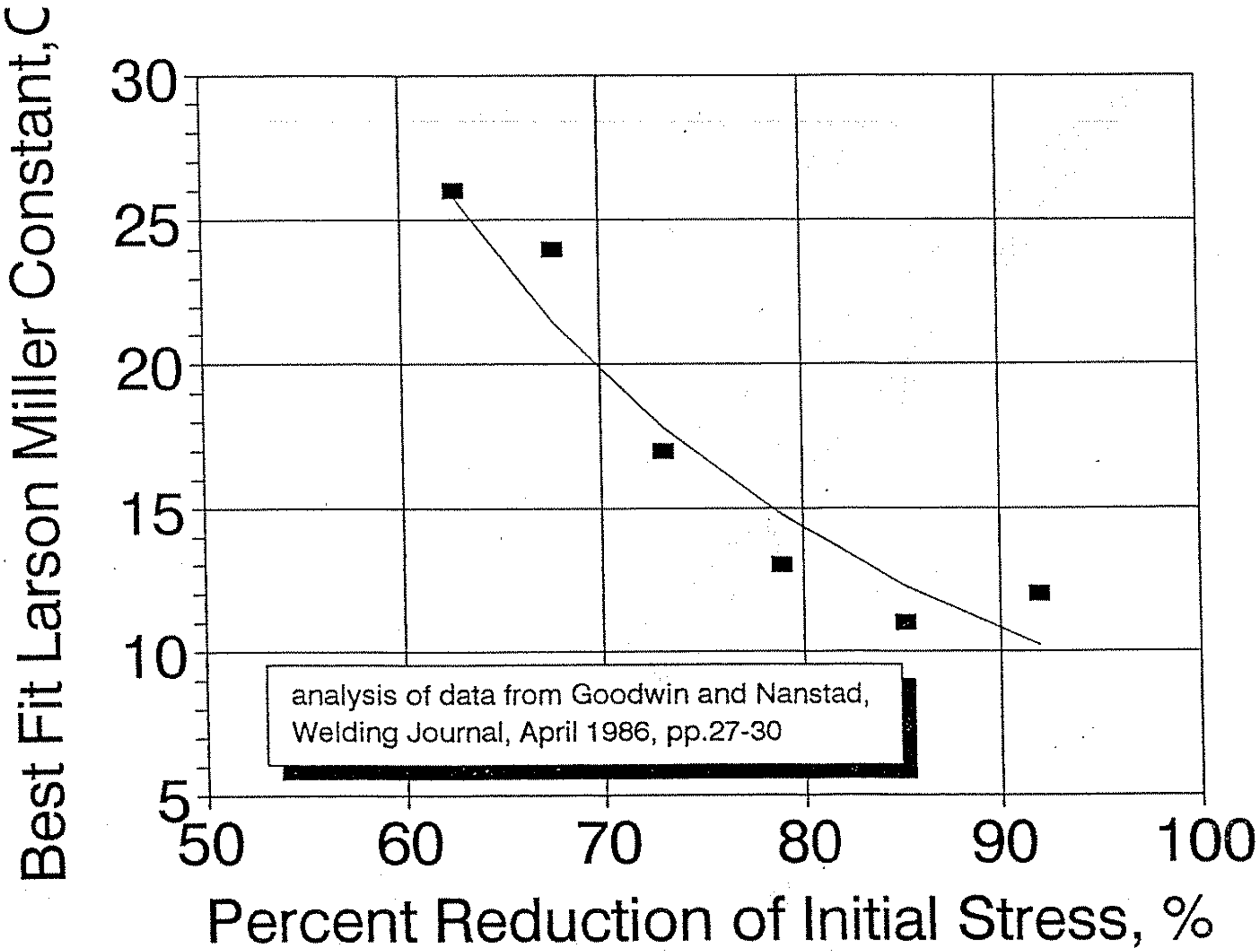


Figure 2: Best fit Larson-Miller C constant for stress relaxation data from ref. [8]

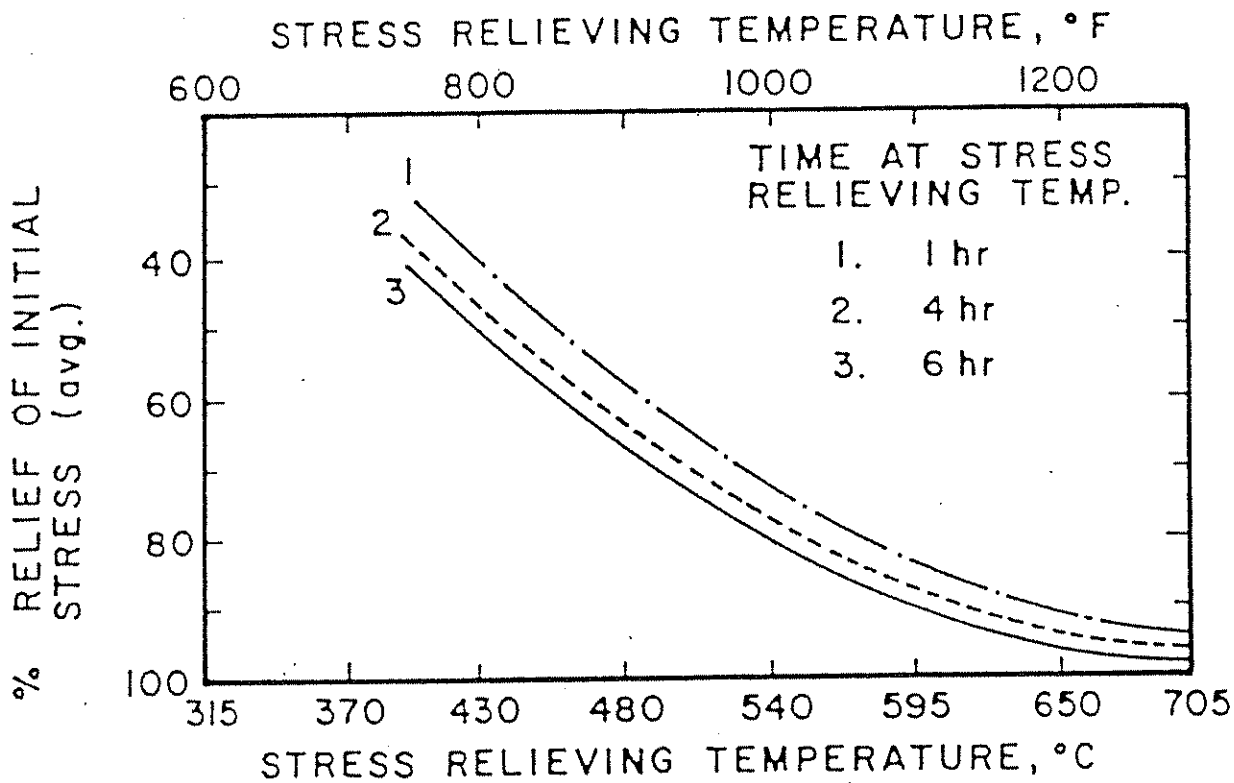


Figure 3: Effect of temperature and time on the relief of residual stresses in a carbon steel, from references [9].

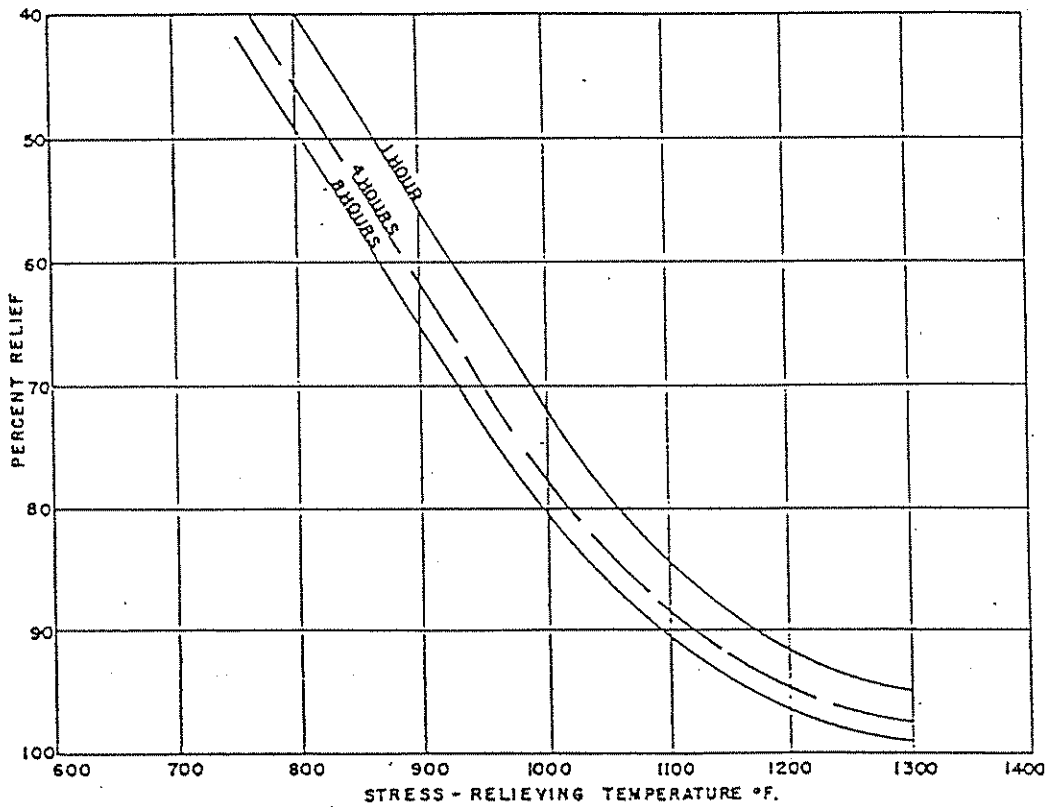
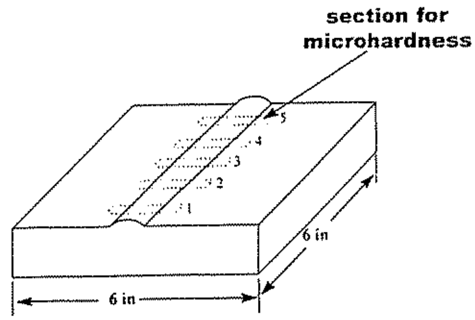
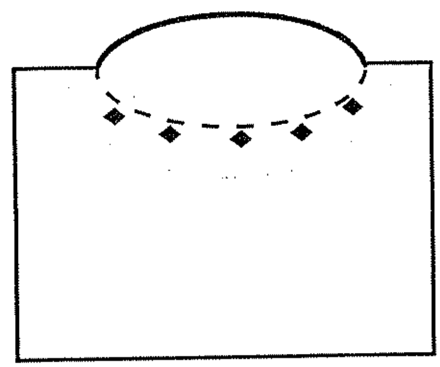
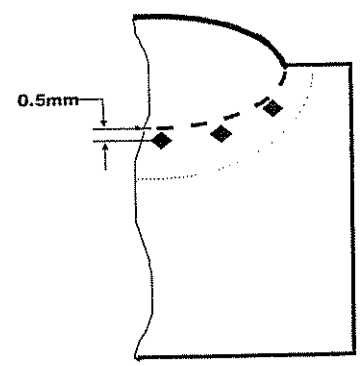


Figure 4: Effect of temperature and time on the relief of residual stresses in a carbon steel casting, from reference [10].





HAZ hardness determination



DPH 1kg load within 0.5mm of fusion line in HAZ
Five readings each section
Five sections each PWHT

Figure 5: Sketches showing the method for monitoring HAZ hardness, adapted from the procedure of Graville [17].

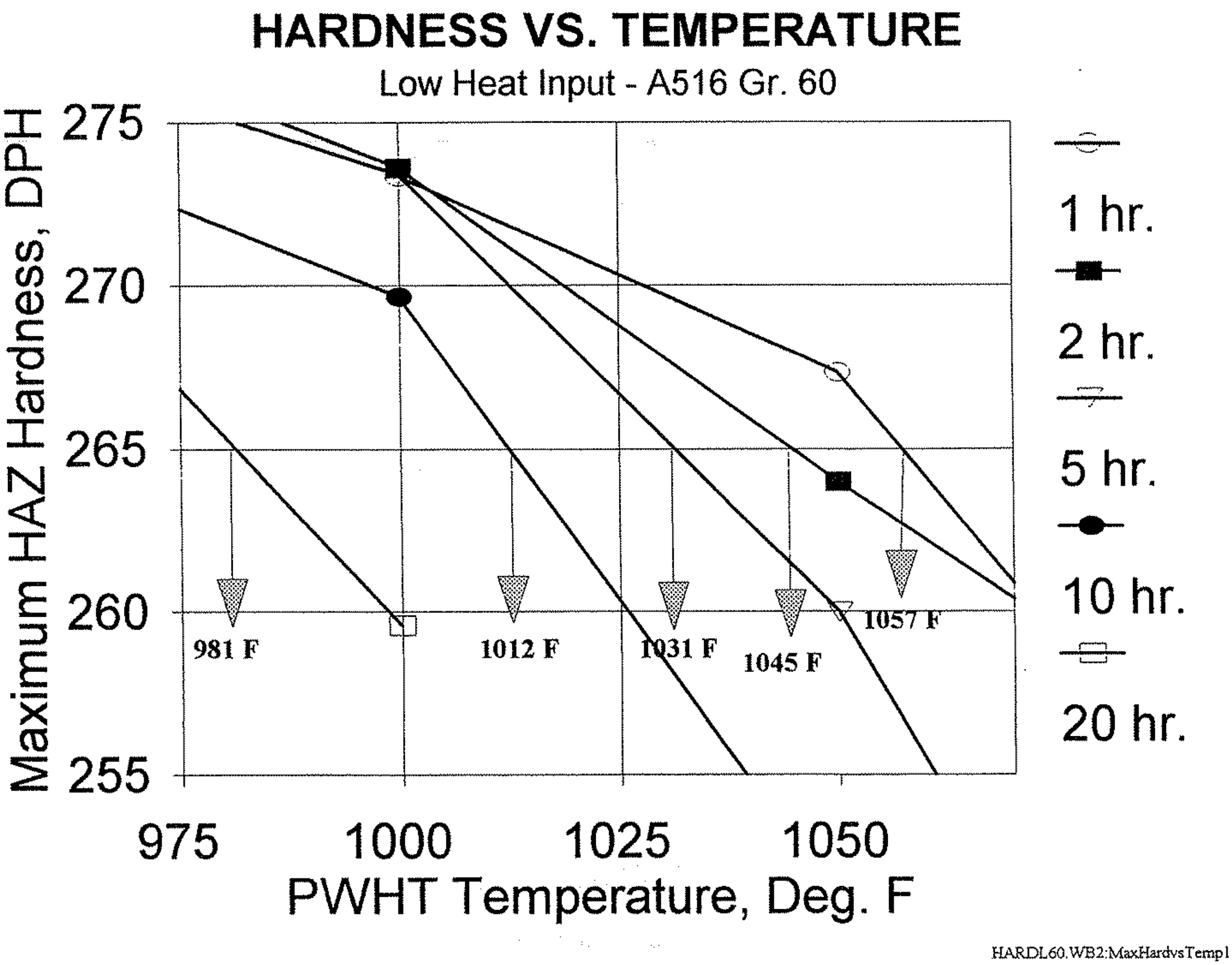


Figure 6a: Plot illustrating how the data is examined to determine time-temperture combinations which yield HAZ hardness equivalency.

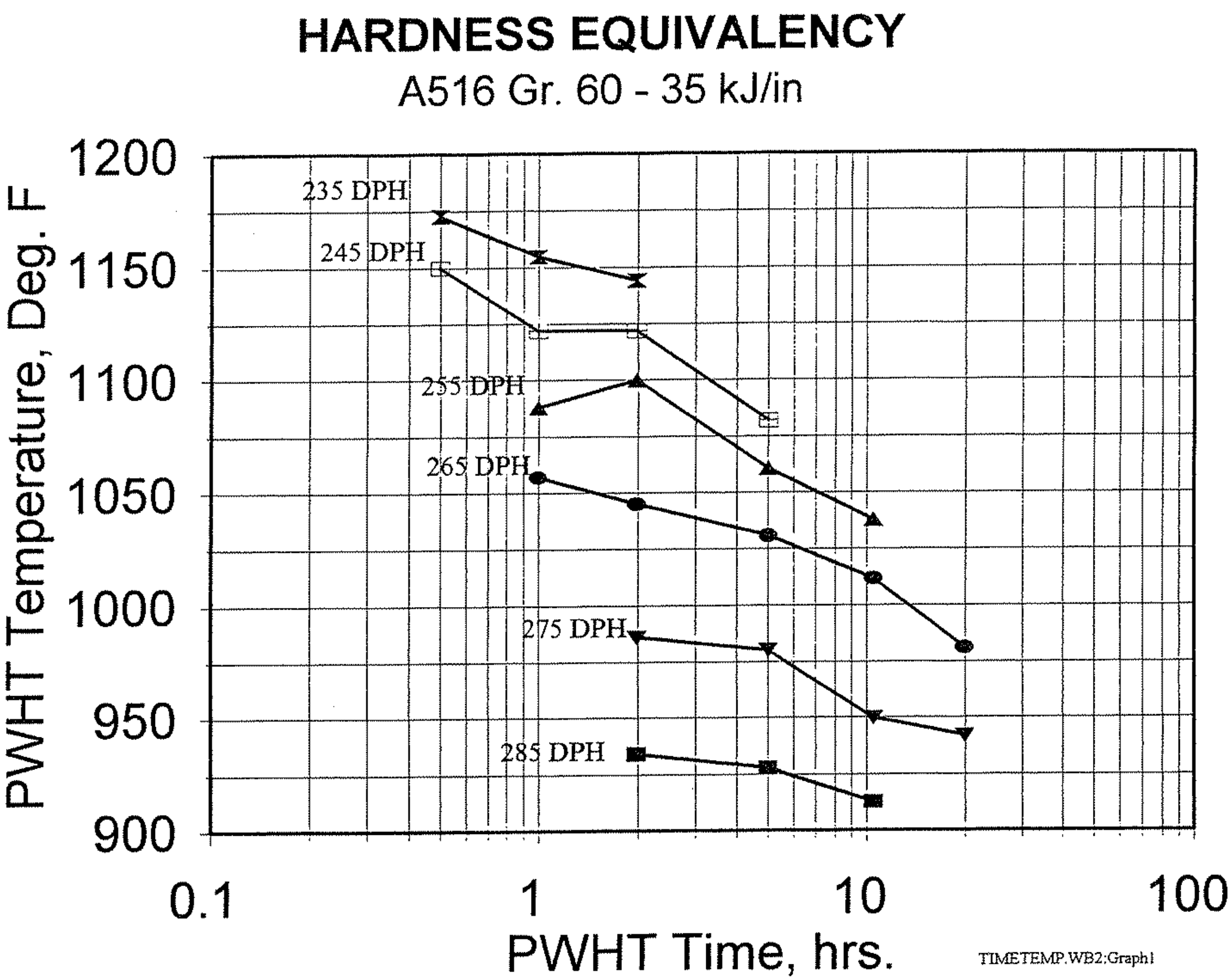


Figure 6b: Plot illustrating the time-temperature combinations giving HAZ hardness equivalency.

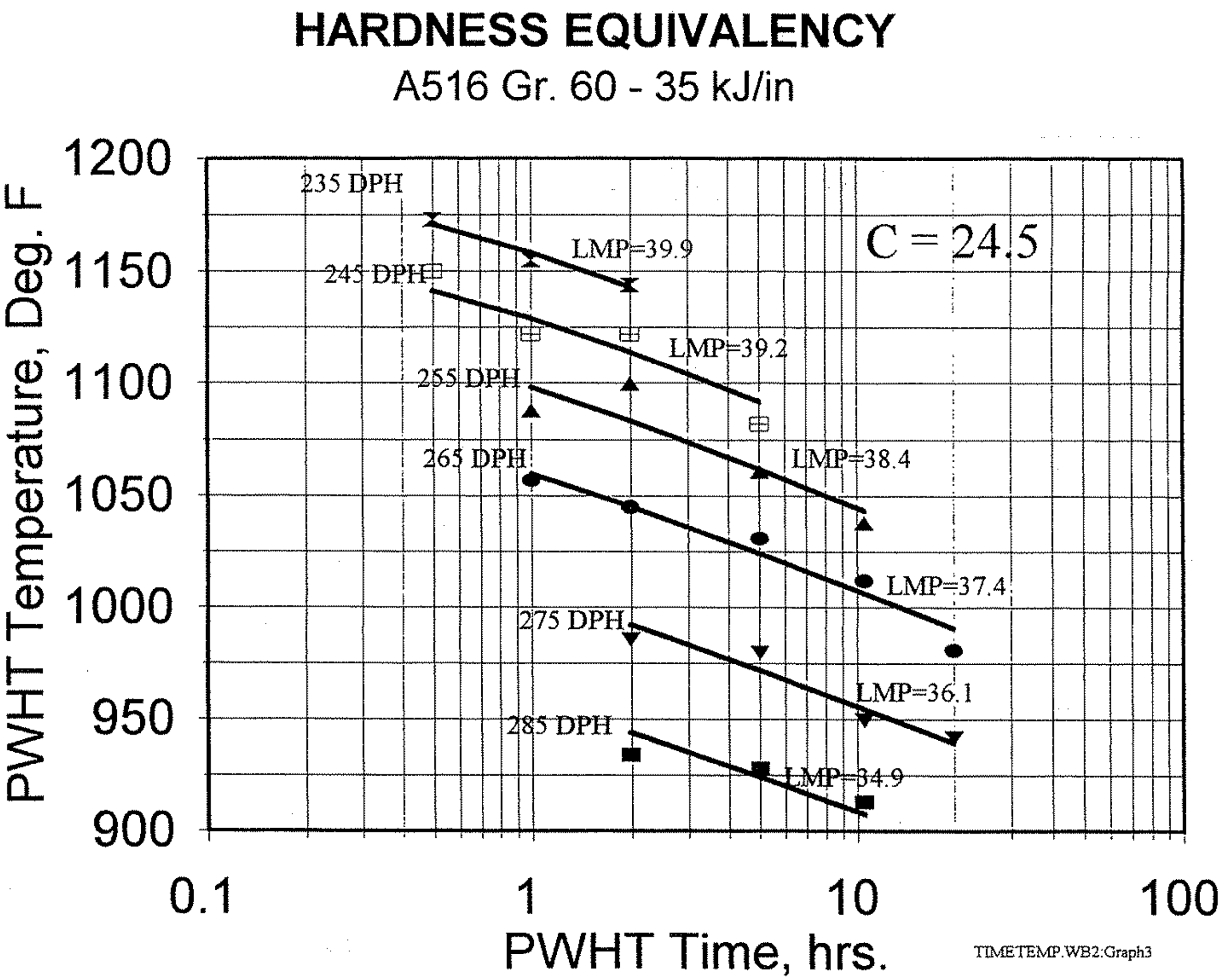


Figure 6c: Plot showing data from Figure 6b now modeled with a Larson-Miller parametric analysis using the best fit C constant.

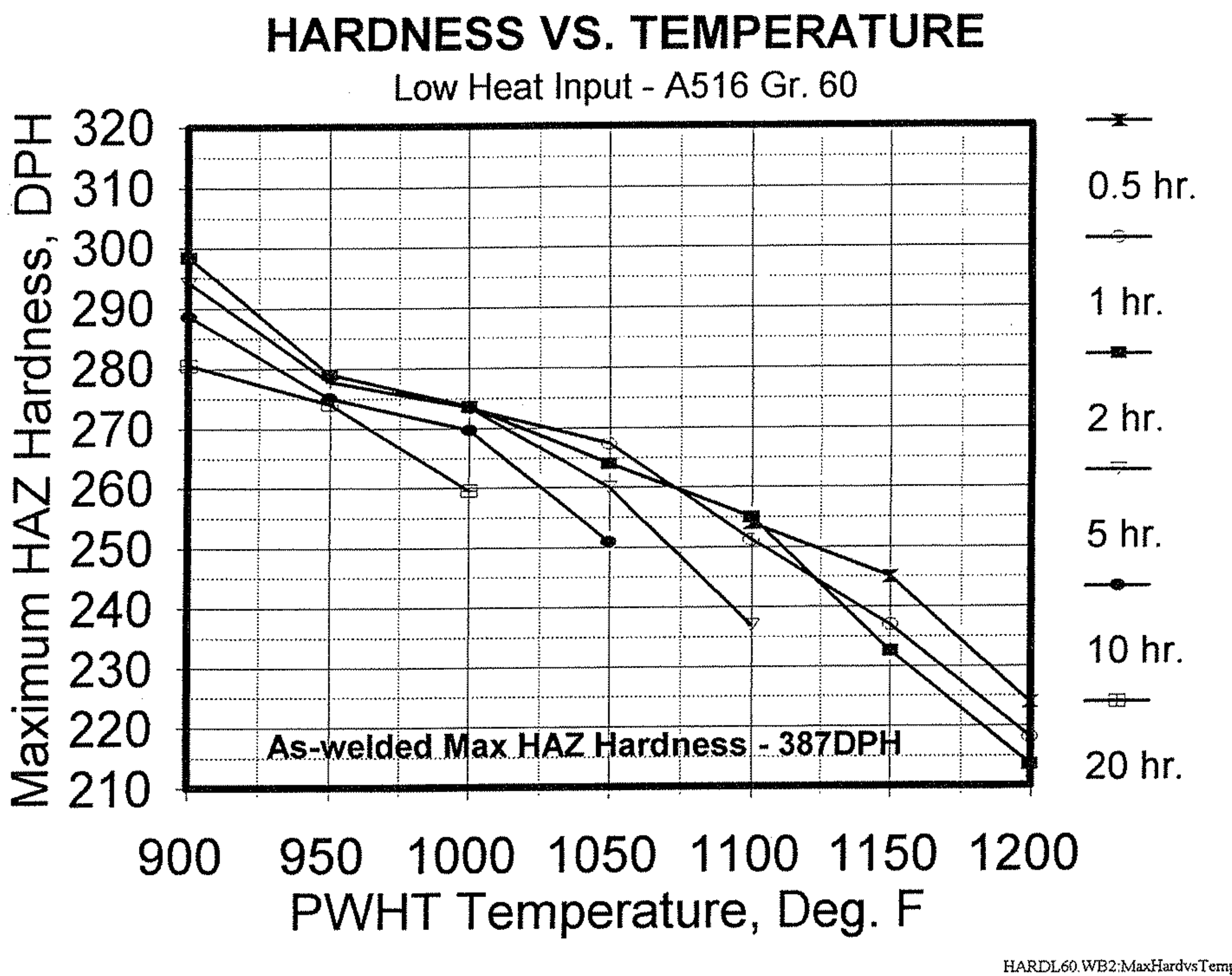


Figure 7: PWHT softening of A516 Grade 60, 35kJ/in HAZ.
Diamond Pyramid Hardness - 1 kg load

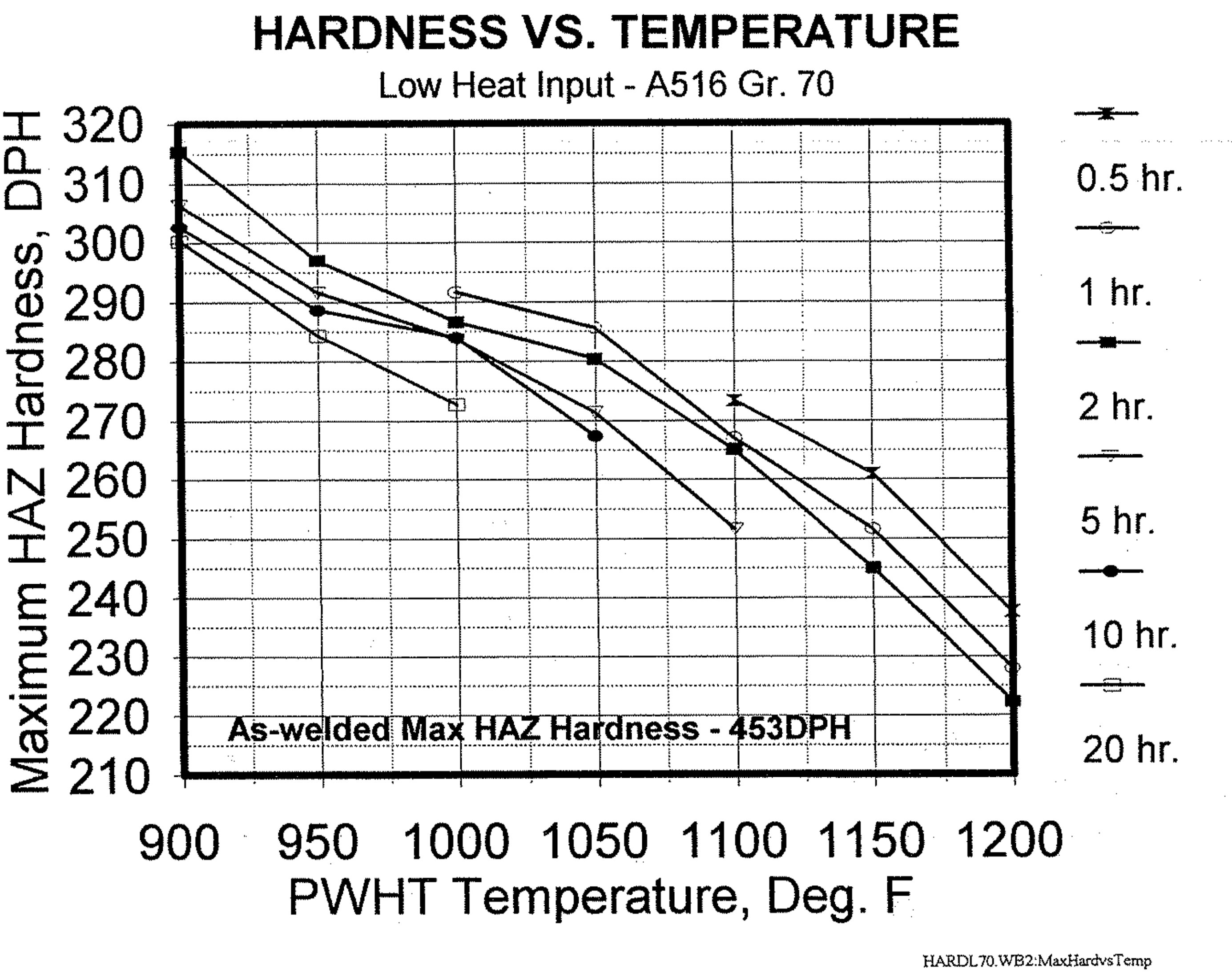


Figure 8: PWHT softening of A516 Grade 70, 35kJ/in HAZ.
Diamond Pyramid Hardness - 1 kg load

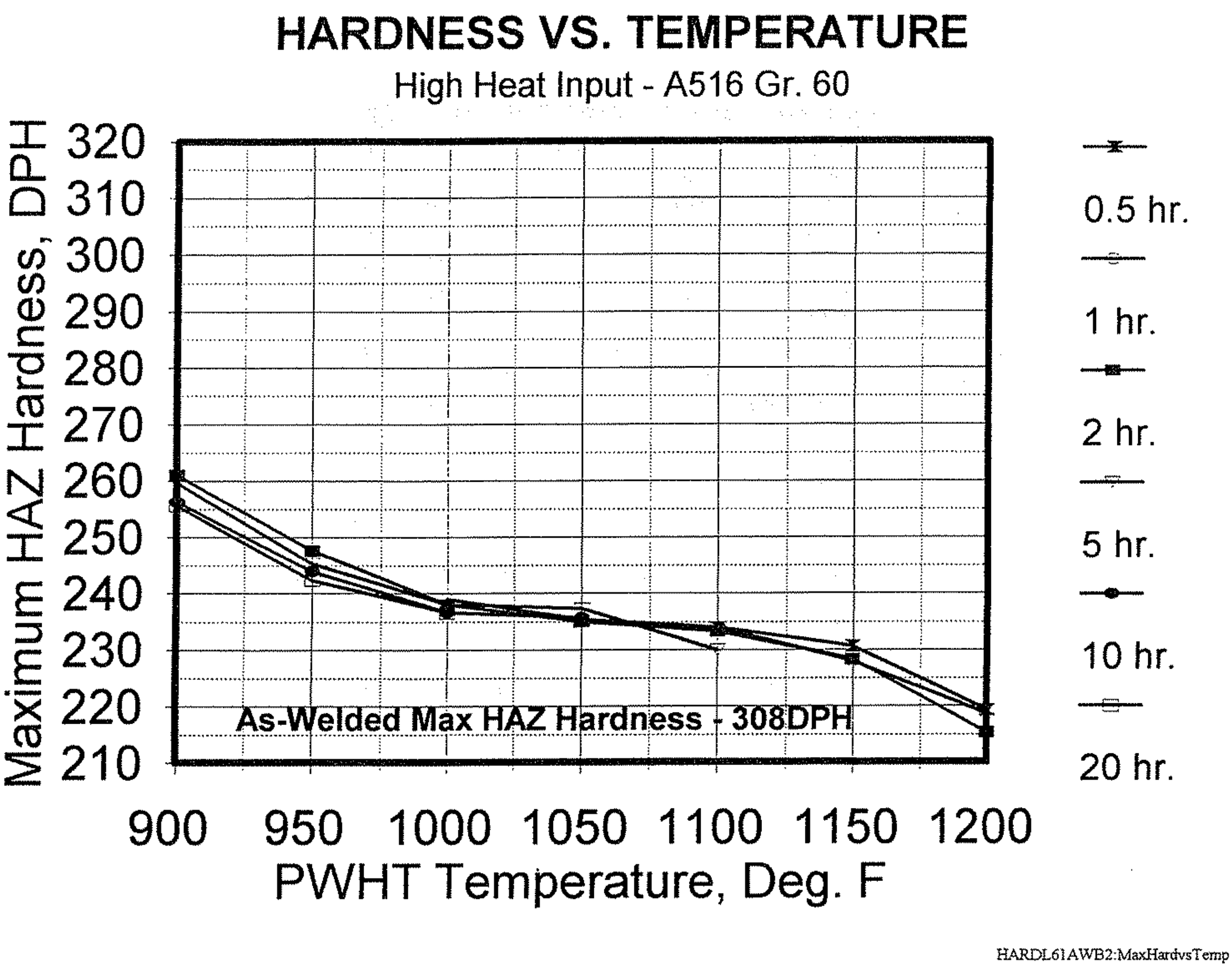


Figure 9: PWHT softening of A516 Grade 60, 125kJ/in HAZ.
Diamond Pyramid Hardness - 1 kg load

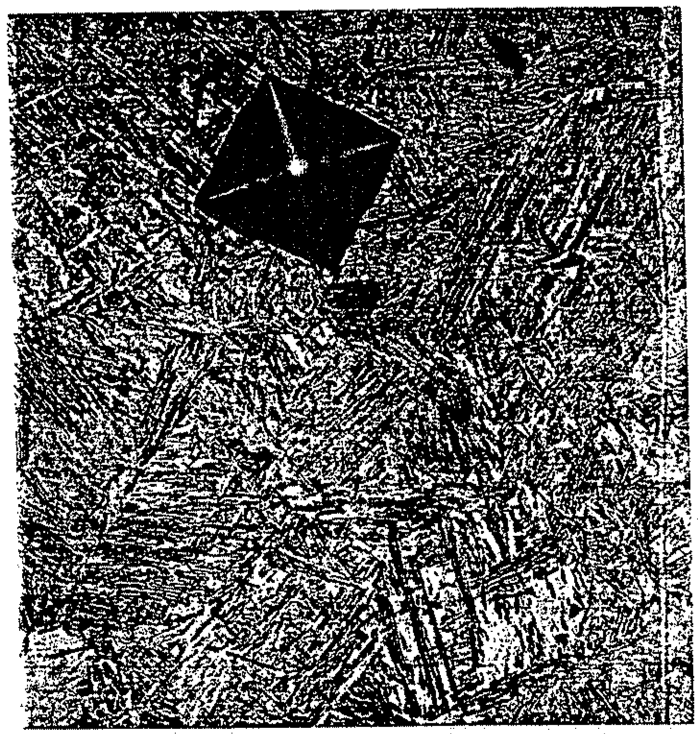


Figure 10: Photomicrograph showing HAZ region of 35 kJ/in A516 Grade 60 weldment in as-welded condition. DPH microhardness impression is visible in the HAZ.
Etchant: Nital Magnification: 400X

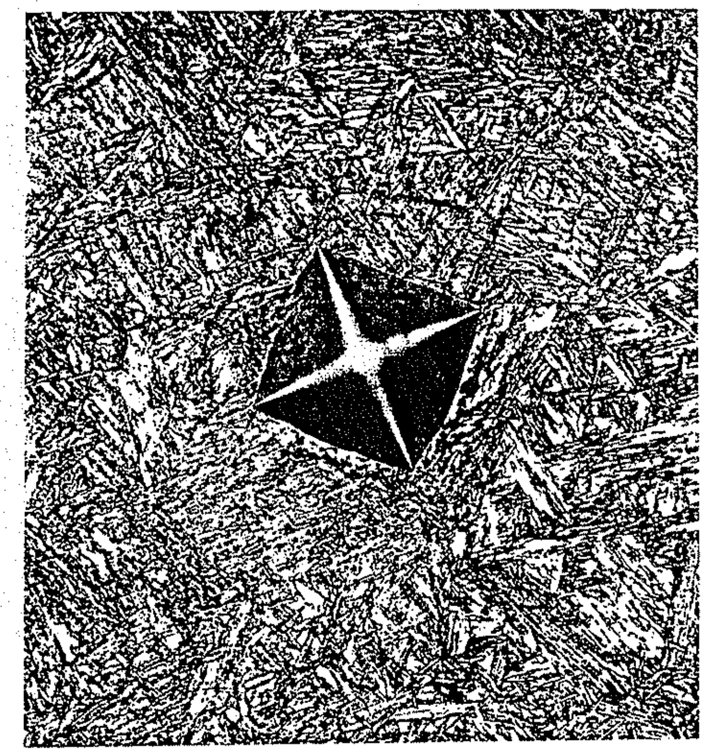


Figure 11: Photomicrograph showing HAZ region of 35 kJ/in A516 Grade 60 weldment; PWHT - 1 hour at 1000°F. DPH microhardness impression is visible in the HAZ.
Etchant: Nital Magnification: 400X

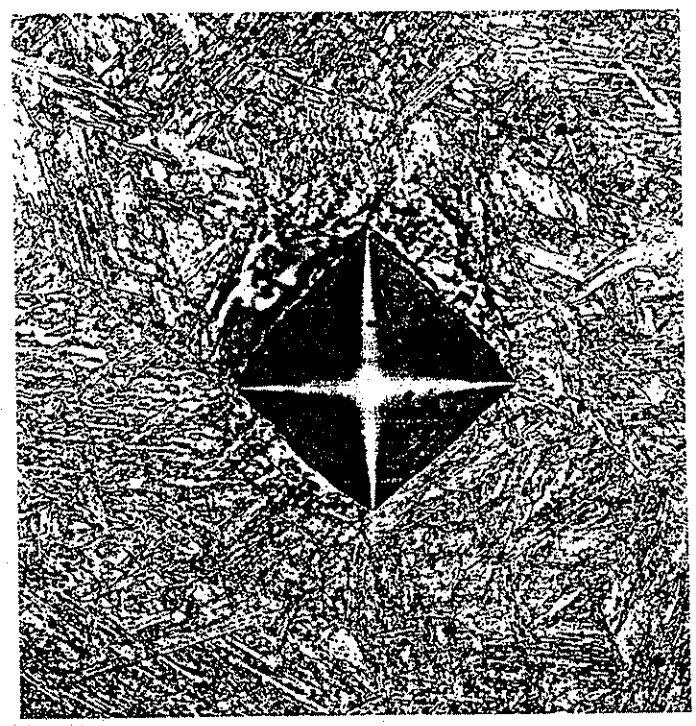


Figure 12: Photomicrograph showing HAZ region of 35 kJ/in A516 Grade 60 weldment; PWHT - 20 hours at 1200°F. DPH microhardness impression is visible in the HAZ.
Etchant: Nital Magnification: 400X

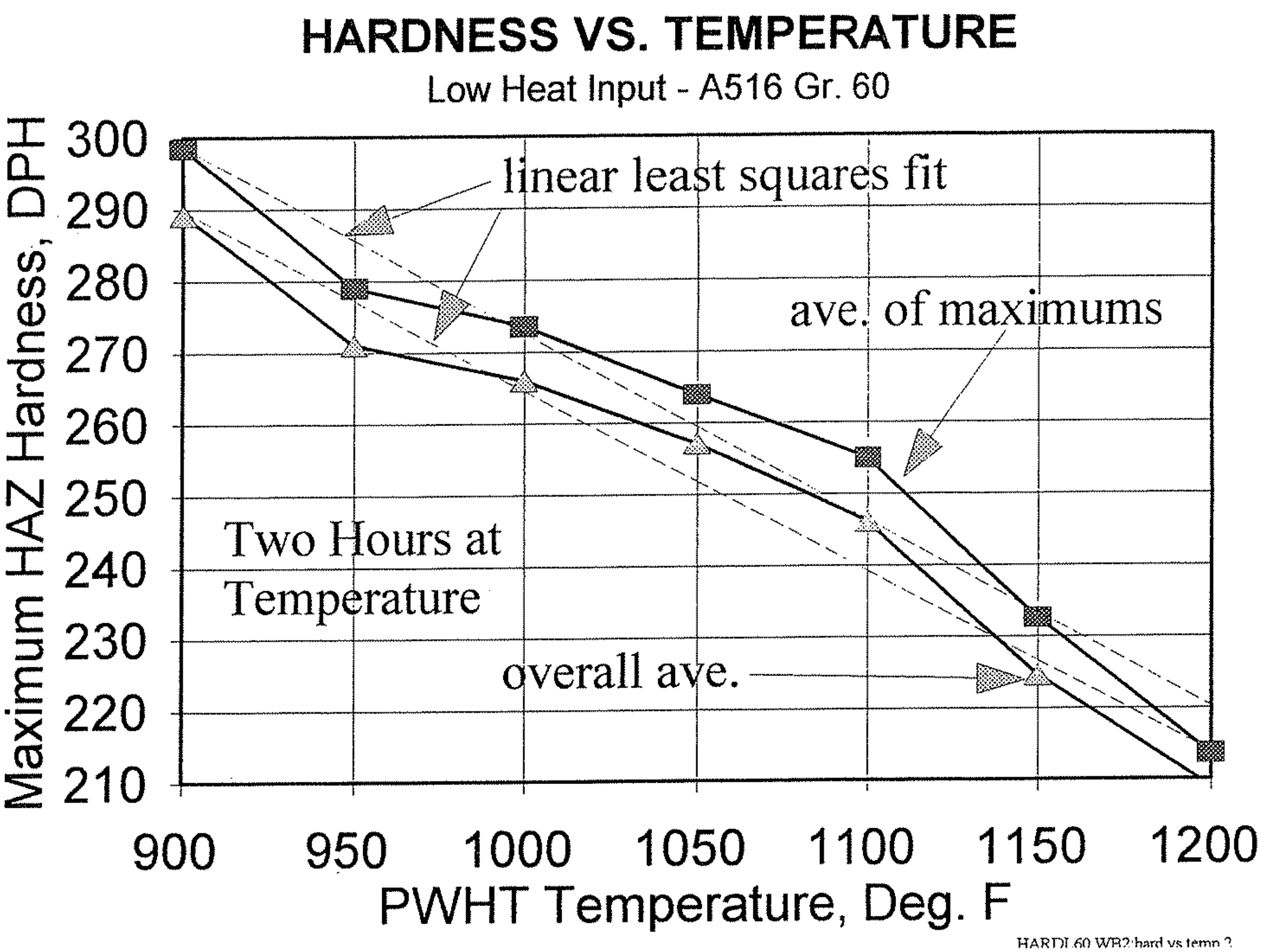


Figure 13: Plot showing comparison of average of maximum of maximum data with the overall average of all maximum HAZ hardness data for two hour PWHT in the A516 Grade, 35kJ/in HAZ.

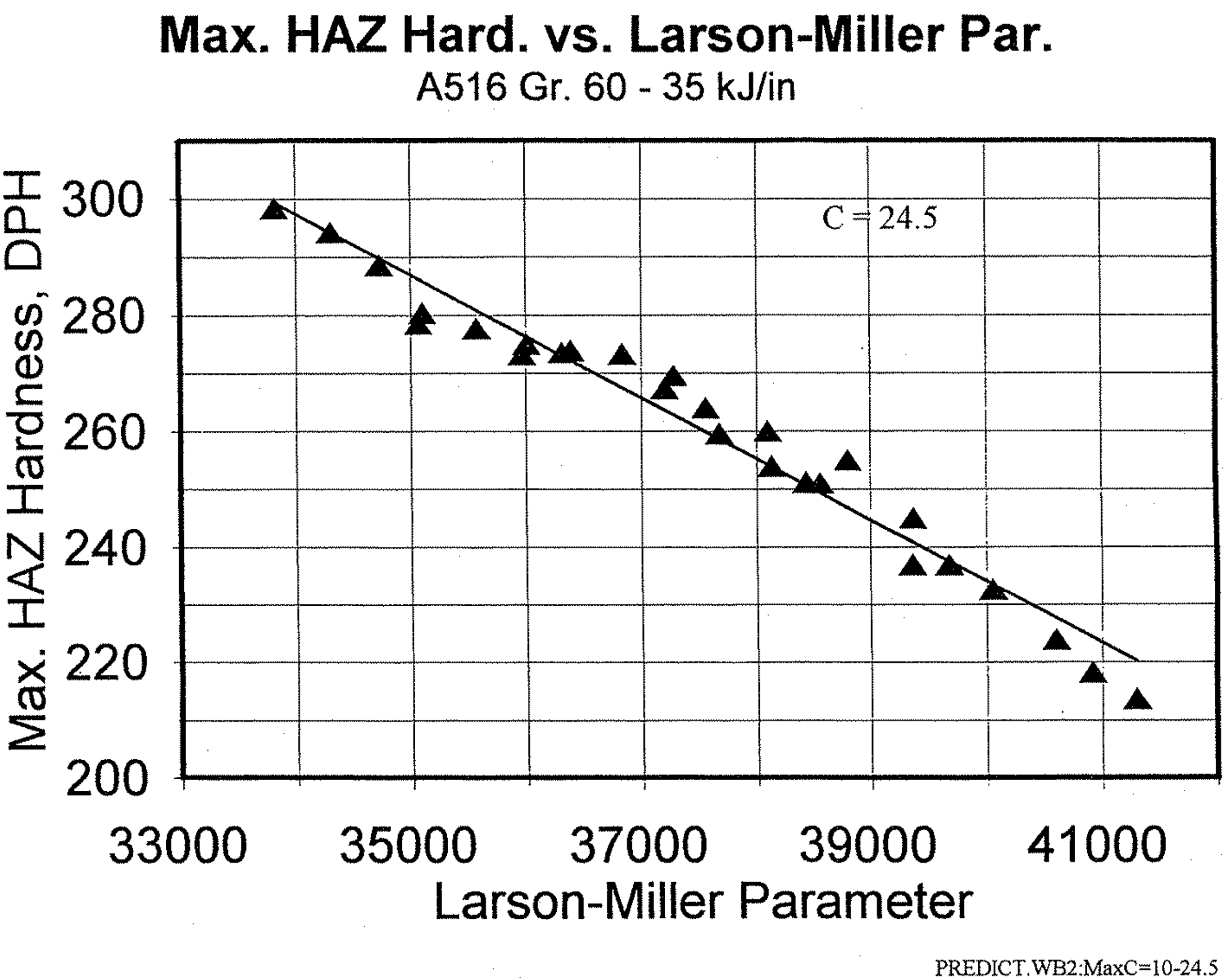
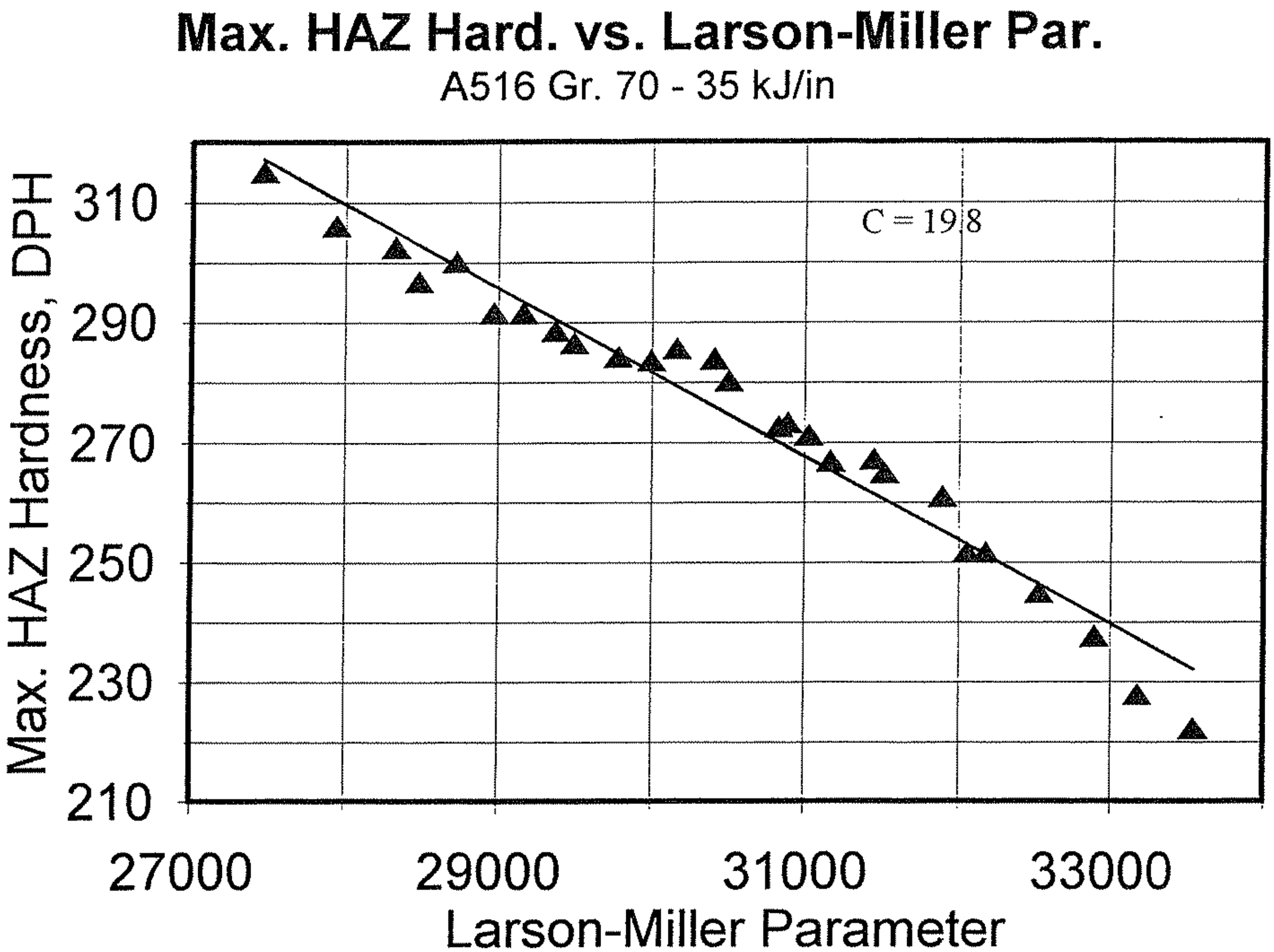


Figure 14: Plot of HAZ hardness versus Larson-Miller parameter using best fit C value, C=24.5, for A516 Grade 60, 35 kJ/in HAZ.



PREDICT.WB2:C=20/GR70LO

Figure 15: Plot of HAZ hardness versus Larson-Miller parameter using best fit C value, C=19.8, for A516 Grade 70, 35 kJ/in HAZ.

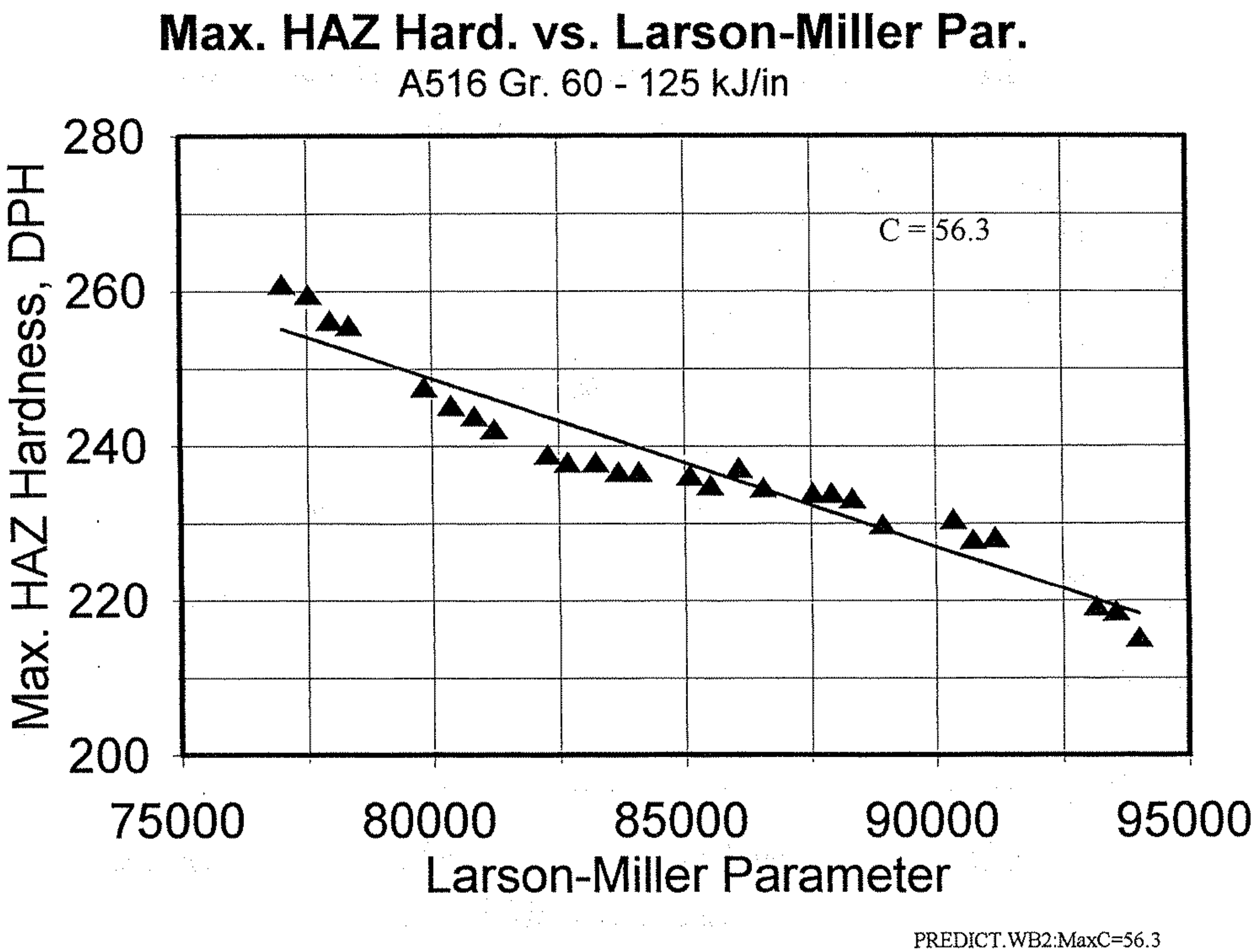


Figure 16: Plot of HAZ hardness versus Larson-Miller parameter using best fit C value, C=56.3, for A516 Grade 60, 125 kJ/in HAZ.

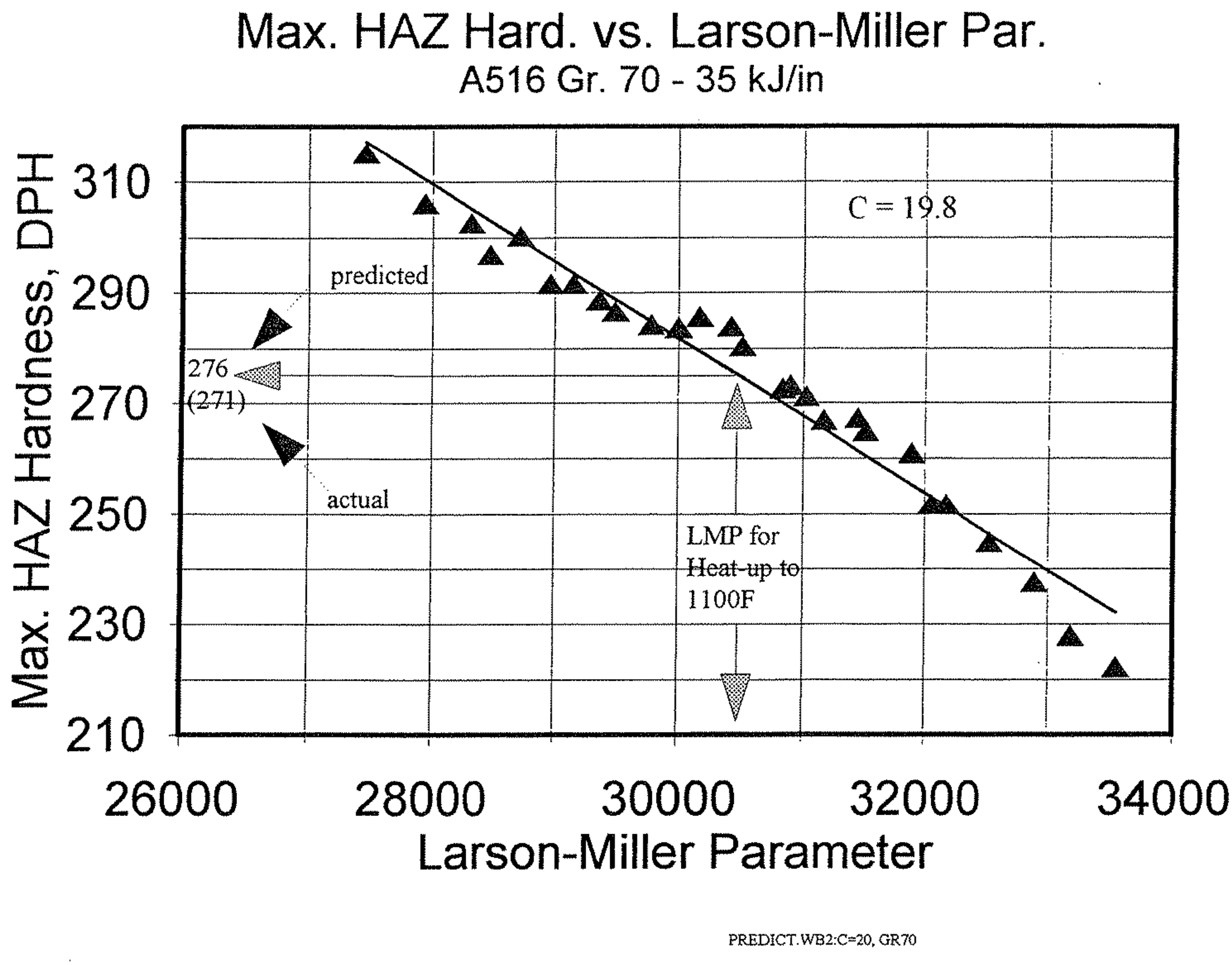


Figure 17: Plot illustrating the prediction of HAZ hardness after ramp heat-up to 1100°F at 78°F/hr. The effective time for this heat-up is 0.485 hour at 1100°F which yields a Larson-Miller parameter of 30,450.

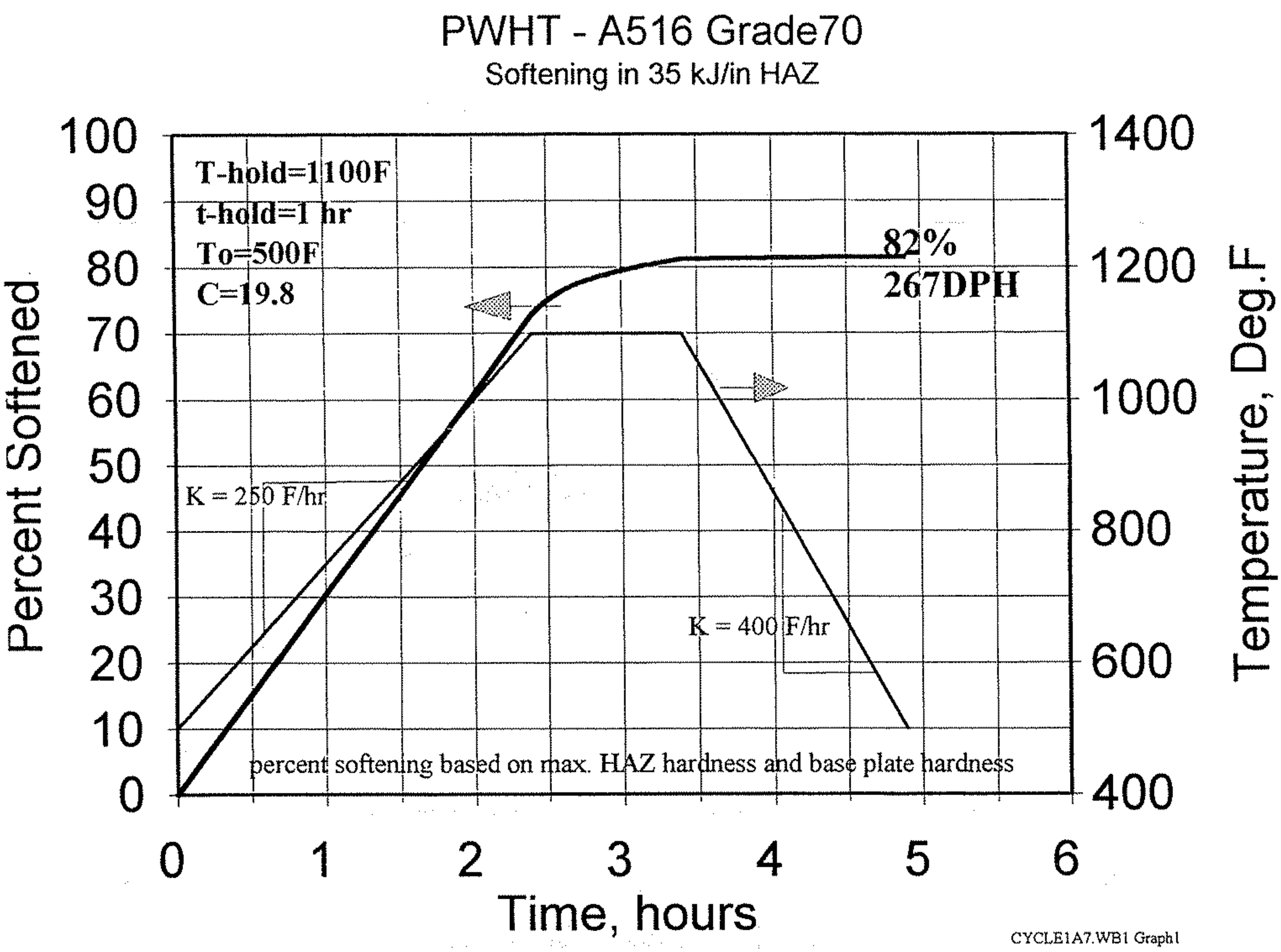


Figure 18: Predicted softening due to PWHT of 1 hour at 1100°F for an A516 Grade 70, 35kJ/in weldment. Heat-up rate = 250°F/hr.

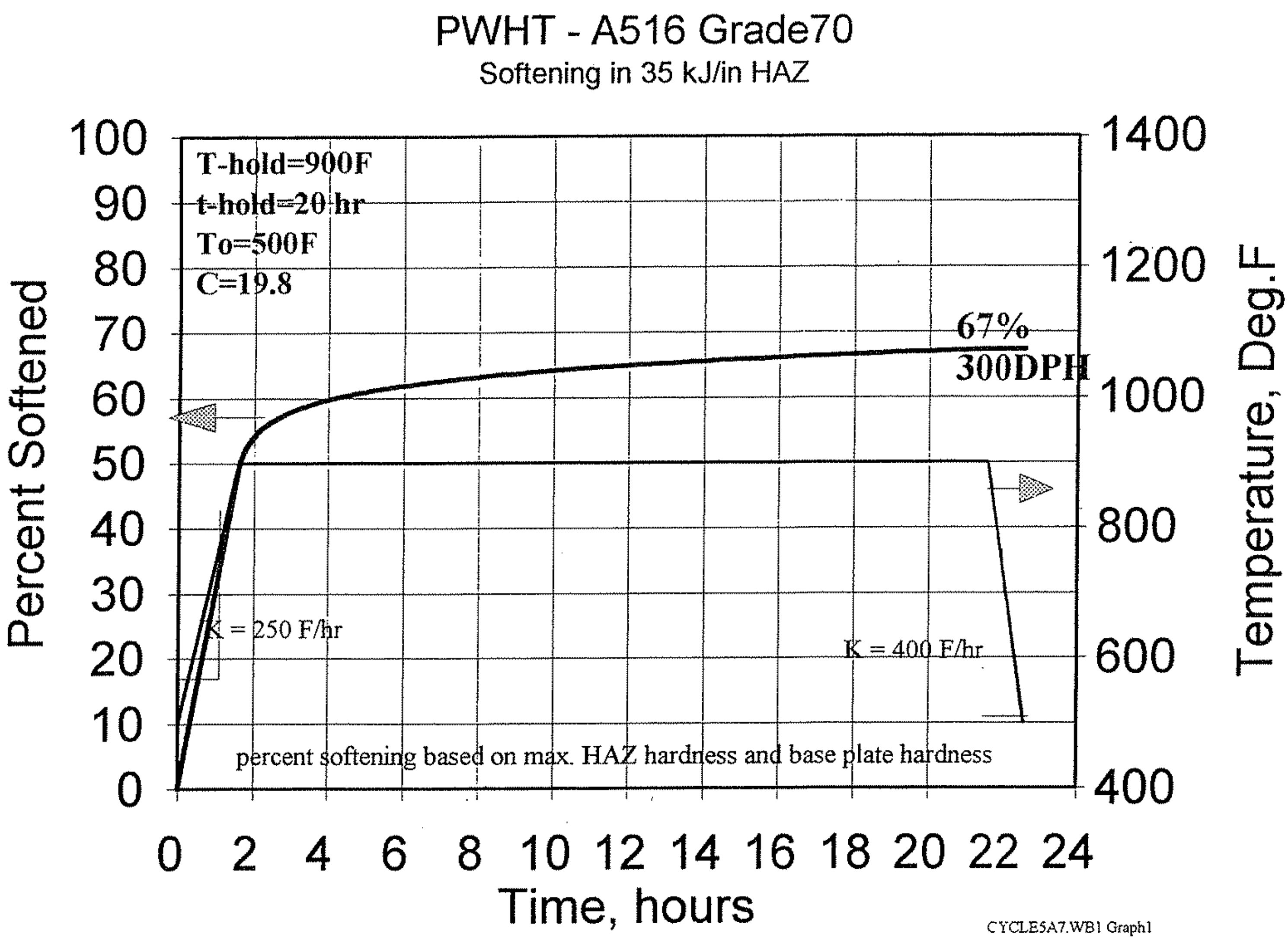


Figure 19: Predicted softening due to PWHT of 20 hours at 900°F for an A516 Grade 70, 35kJ/in weldment. Heat-up rate = 250°F/hr.

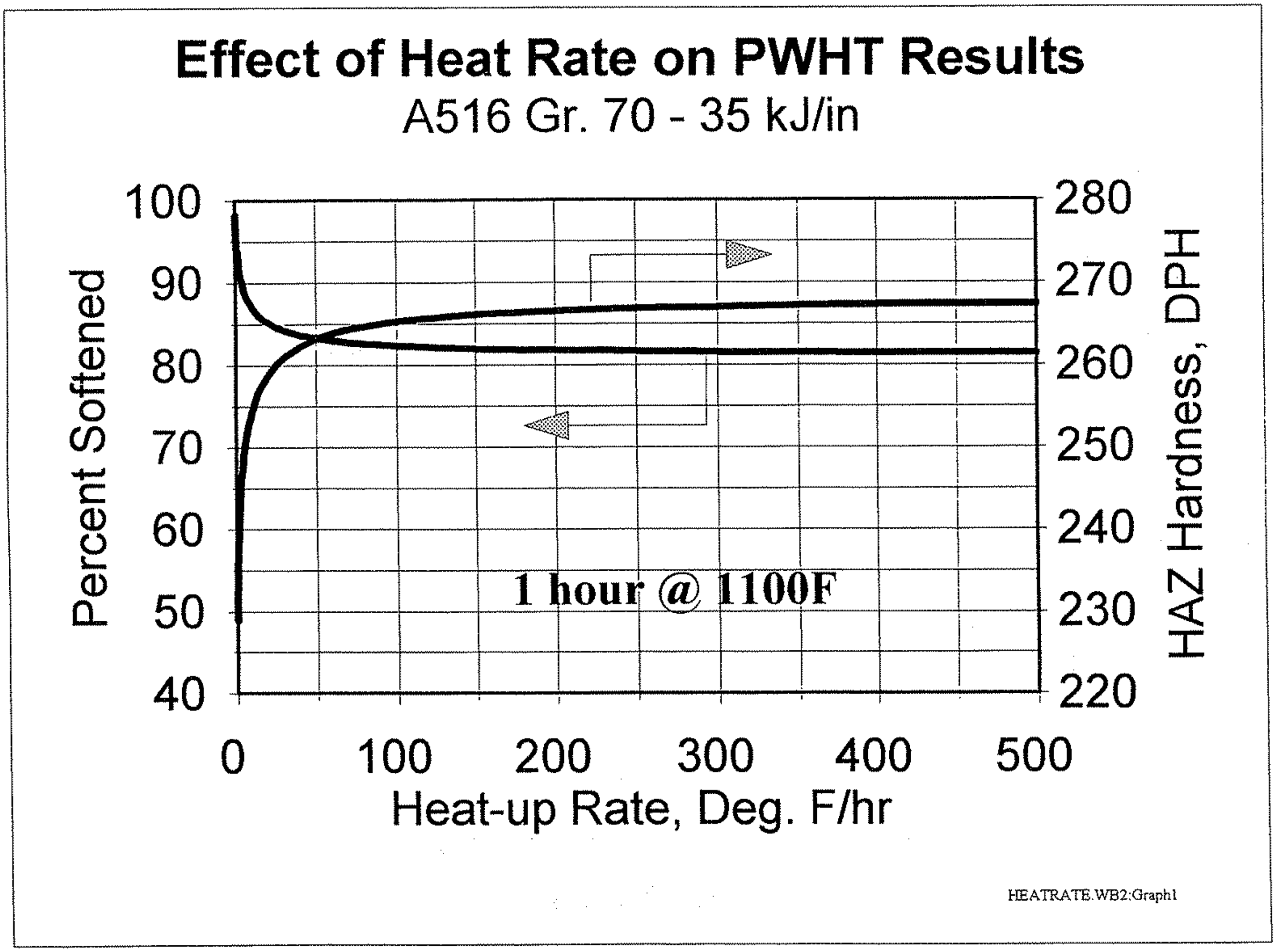


Figure 20: Plot showing the effect of PWHT heat-up rate on predicted HAZ softening of an A516 Grade 70, 35kJ/in weldment.

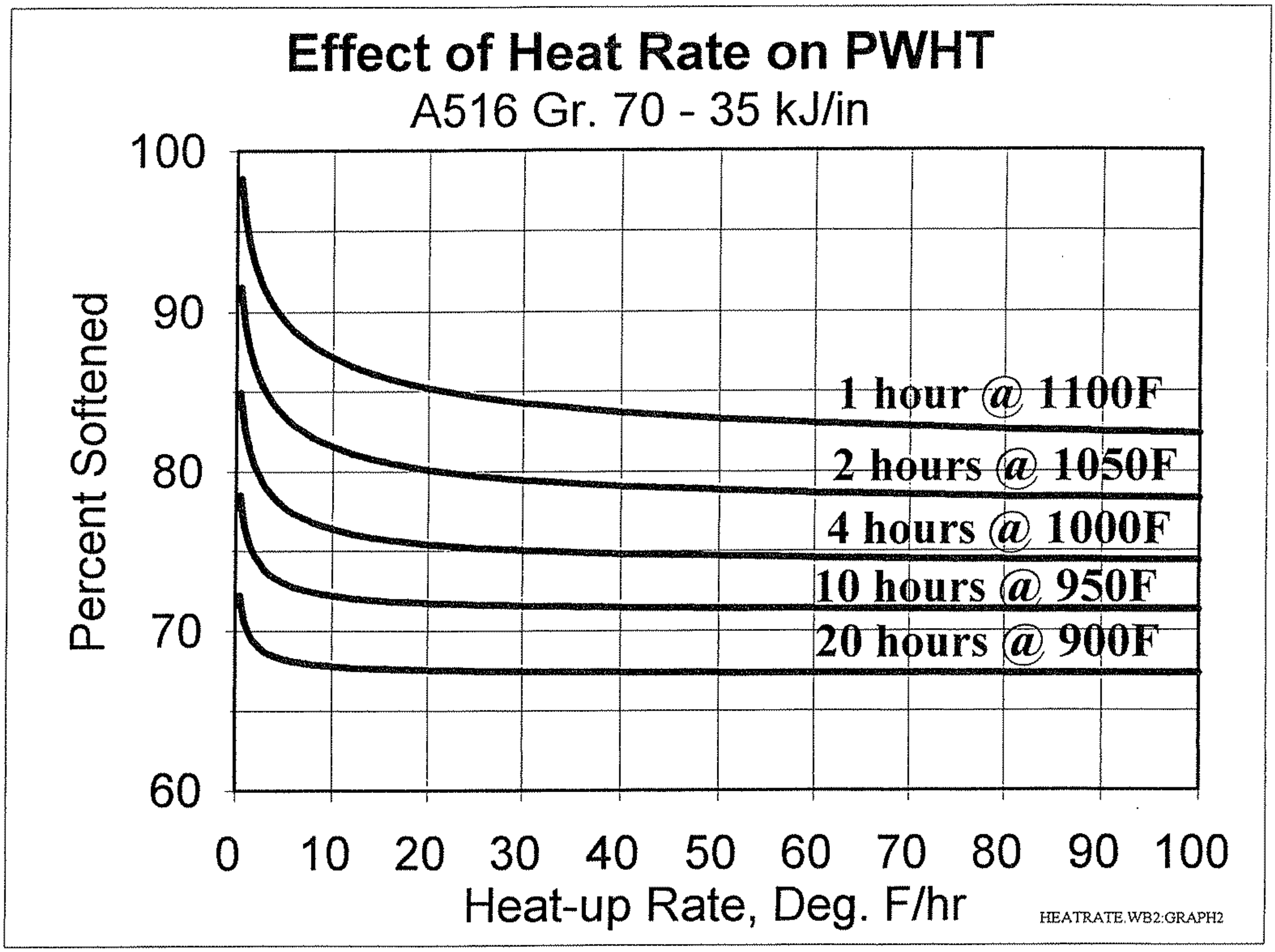


Figure 21: Plot showing the effect of PWHT heat-up rate on predicted HAZ softening of an A516 Grade 70, 35kJ/in weldment.

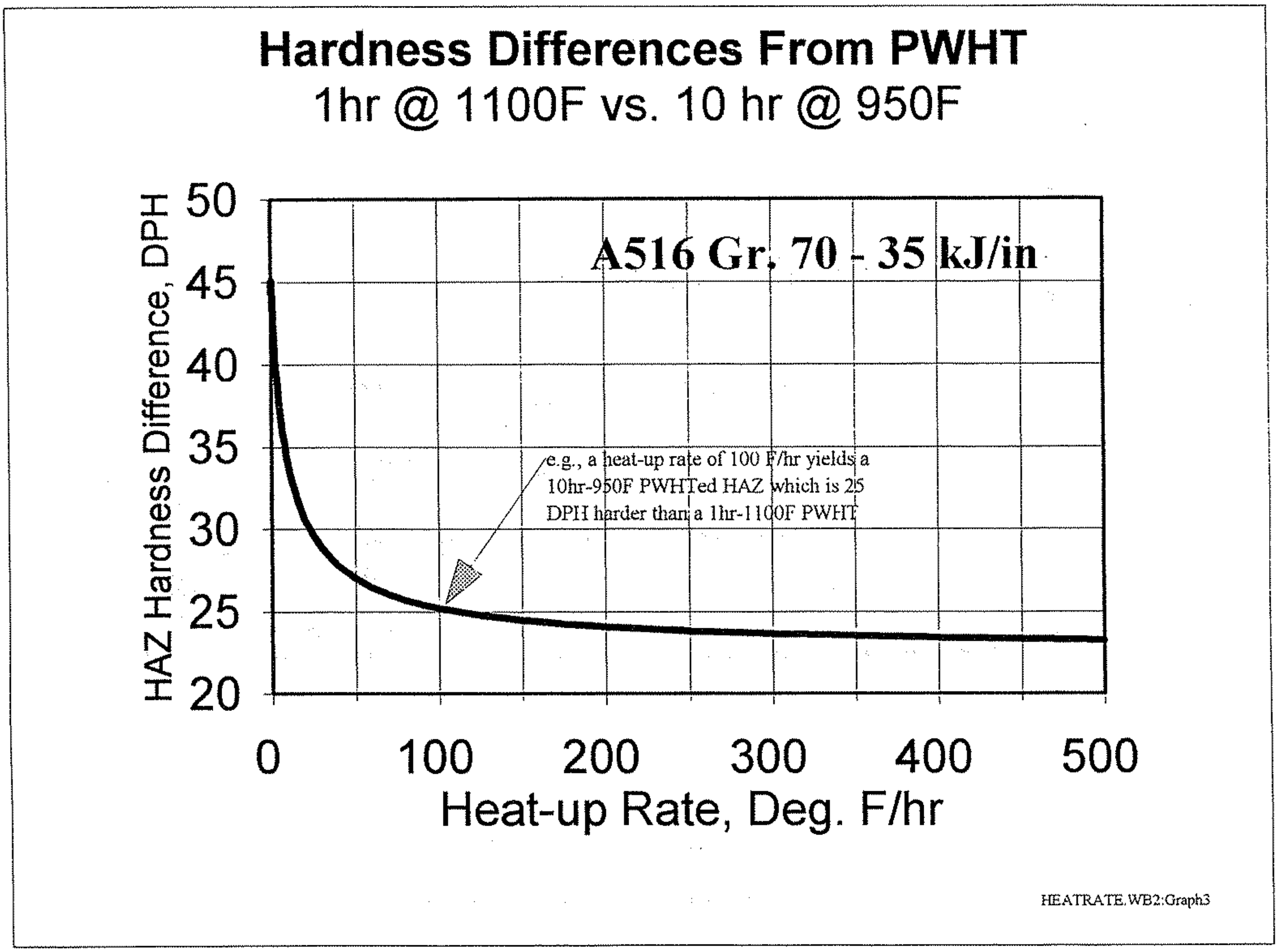


Figure 22: Plot of predicted HAZ hardness difference between a 1 hour - 1100°F and a 10 hour - 950°F PWHT in an A516 Grade 70, 35kJ/in weldment as a function of heat-up rate.

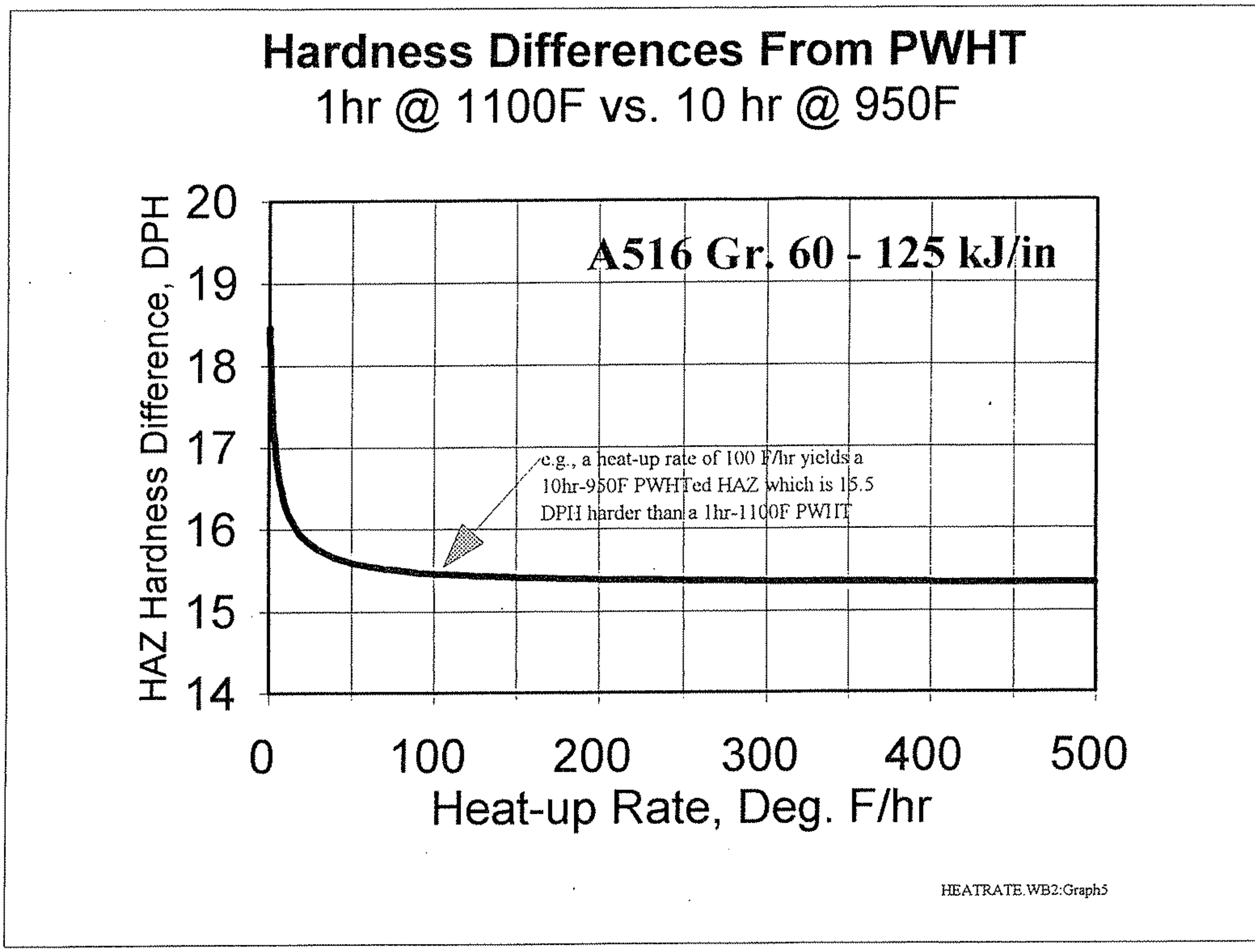


Figure 23: Plot of predicted HAZ hardness difference between a 1 hour - 1100°F and a 10 hour - 950°F PWHT in an A516 Grade 60, 125kJ/in weldment as a function of heat-up rate.

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